

Knowns and unknowns in ν phenomenology



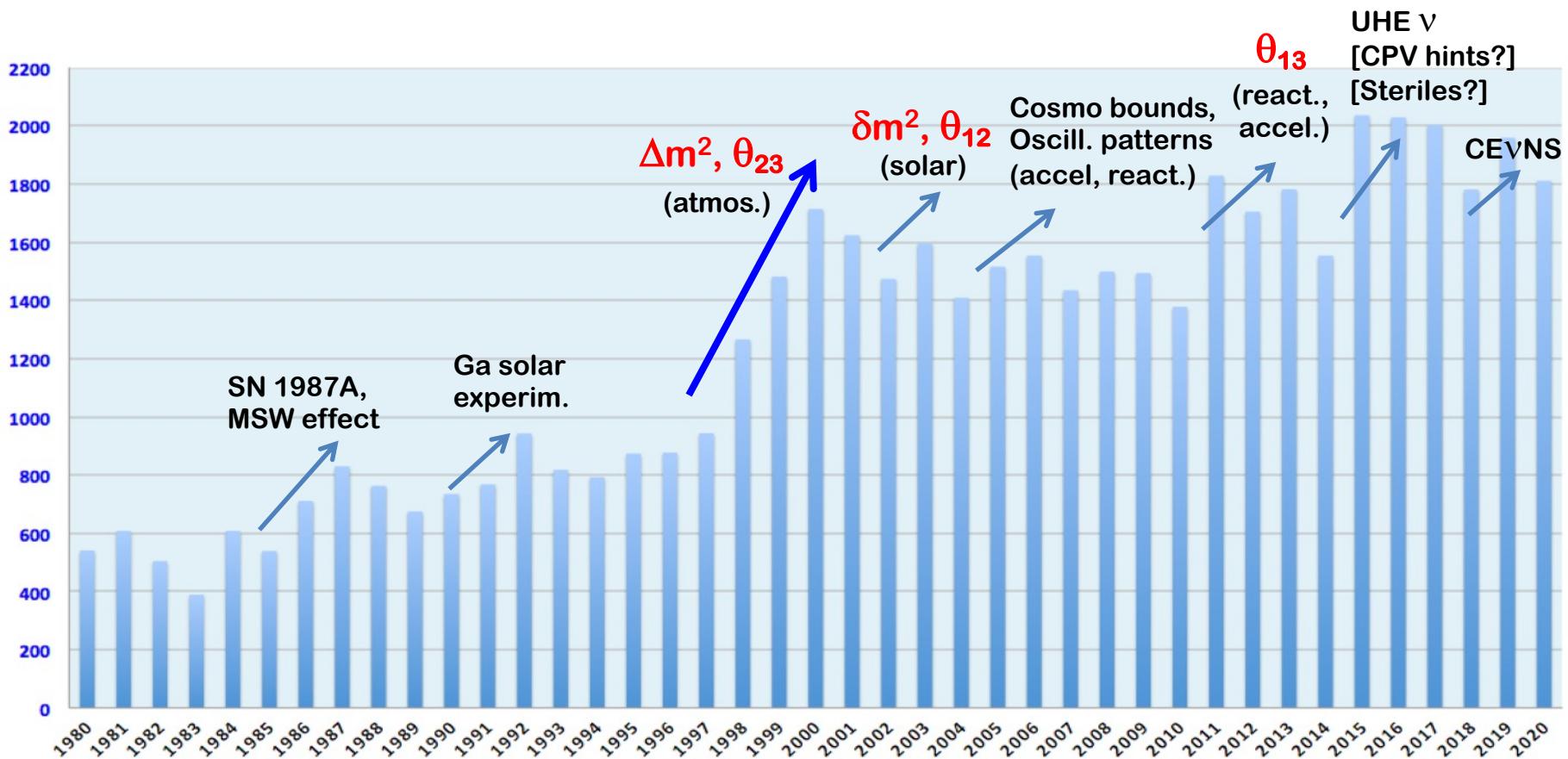
Artwork by Sandbox Studio, Chicago with Ana Kova

Elvio Lisi (INFN Bari)

XXIII Roma Tre Topical Seminar on Subnuclear Physics, 13/12/2021

PROLOGUE

Papers with *neutrino* in the title, 40-yr trend from iNSPIRE 



~2k papers/year, vast phenomenology, multi-disciplinary aspects
Despite the great progress, we still know much less than we would...

Outline

- **3 ν oscillation knowns and unknowns**
- **3 ν nonoscillation unknowns**
- **Context beyond 3 ν**

The standard 3ν framework: parameters

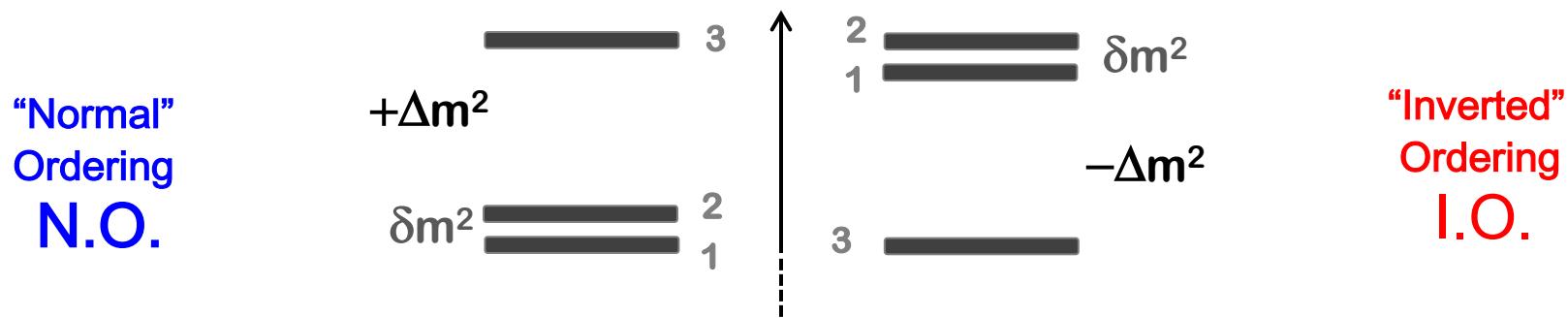
Mixing matrix: CKM → PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation 1-3 rotation
 + CPV “Dirac” phase
 $U(\nu) \rightarrow U^*(\bar{\nu})$ 1-2 rotation Extra CPV phases
 [if Majorana]
 not tested in oscillat.

Mass [squared] spectrum

($E \sim p + m^2/2E + \text{“interaction energy”}$)

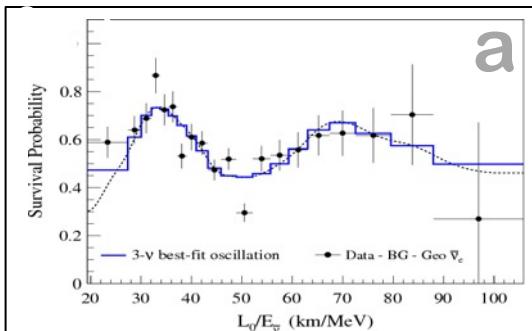


$$\delta m^2 = \Delta m_{21}^2, \quad \Delta m^2 = (\Delta m_{32}^2 + \Delta m_{31}^2)/2$$

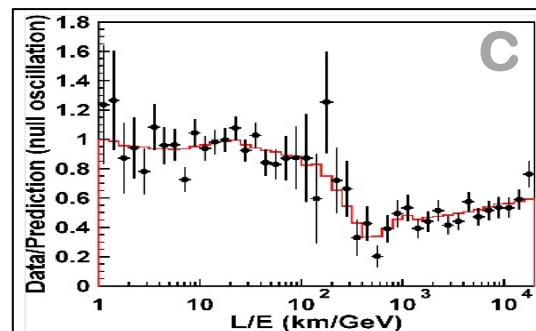
+ interaction energy in matter $\rightarrow \sim G_F \cdot E \cdot \text{density}$
 + absolute ν mass scale (not tested in oscillations)

Beautiful ν oscillation data have established this 3 ν framework...

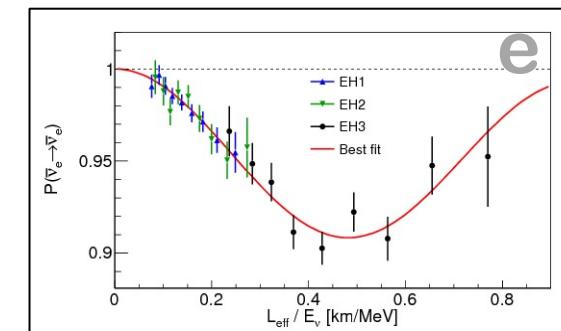
$e \rightarrow e$ (KamLAND, KL)



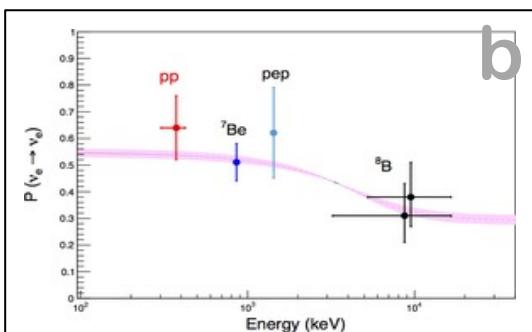
$\mu \rightarrow \mu$ (Atmospheric)



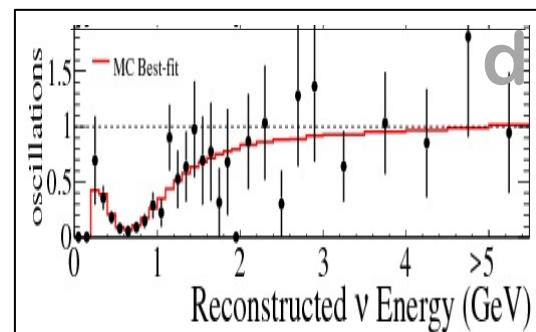
$e \rightarrow e$ (SBL Reac.)



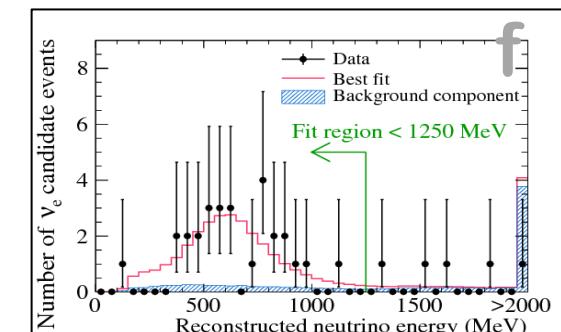
$e \rightarrow e$ (Solar)



$\mu \rightarrow \mu$ (LBL Accel.)



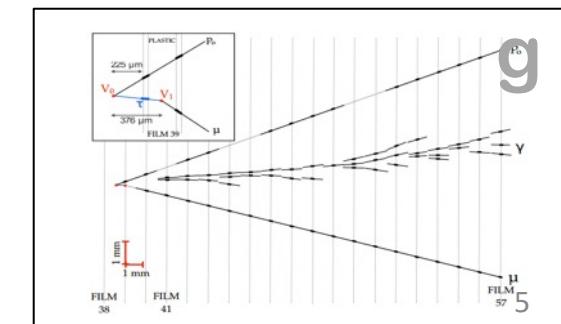
$\mu \rightarrow e$ (LBL Accel.)



LBL = Long baseline (few \times 100 km); SBL = short baseline (\sim 1 km)

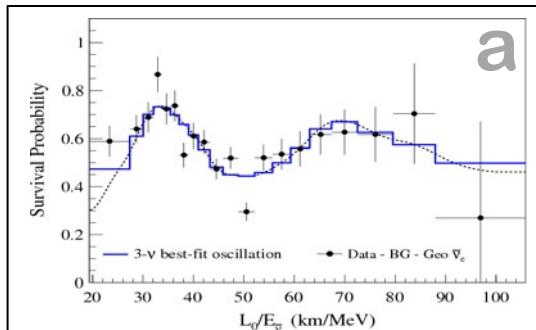
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

$\mu \rightarrow \tau$ (OPERA, SK, DC)

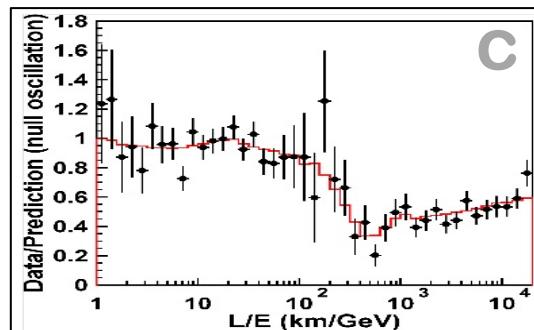


... and consistently measured five ν mass-mixing parameters

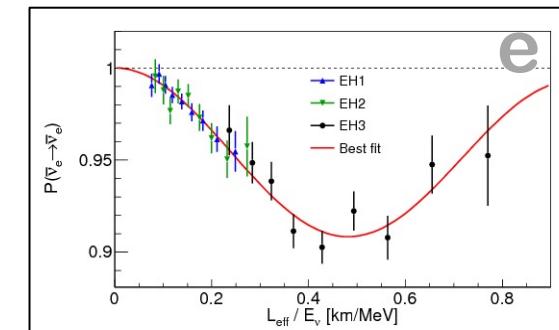
$e \rightarrow e$ (δm^2 , θ_{12})



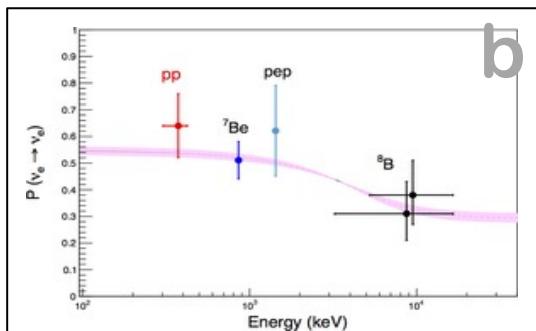
$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



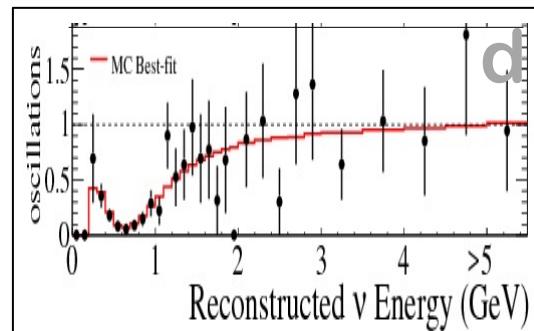
$e \rightarrow e$ (Δm^2 , θ_{13})



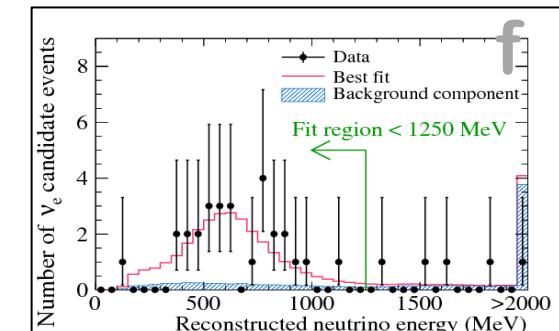
$e \rightarrow e$ (δm^2 , θ_{12})



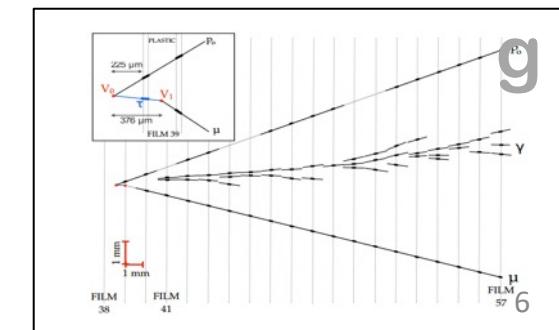
$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



$\mu \rightarrow e$ (Δm^2 , θ_{13} , θ_{23})



$\mu \rightarrow \tau$ (Δm^2 , θ_{23})



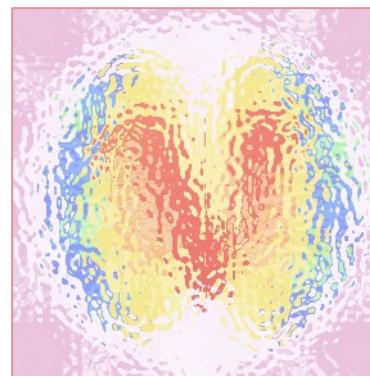
Each leading oscillation parameters (over)constrained by at least two classes of experiments → Consistency

Subleading 3 ν effects involve CPV and NO/IO difference, essentially via $\nu_\mu \rightarrow \nu_e$ in LBL accel. and atmosph. expts

Sketchy 3ν picture (1 significant digit)

5 knowns:

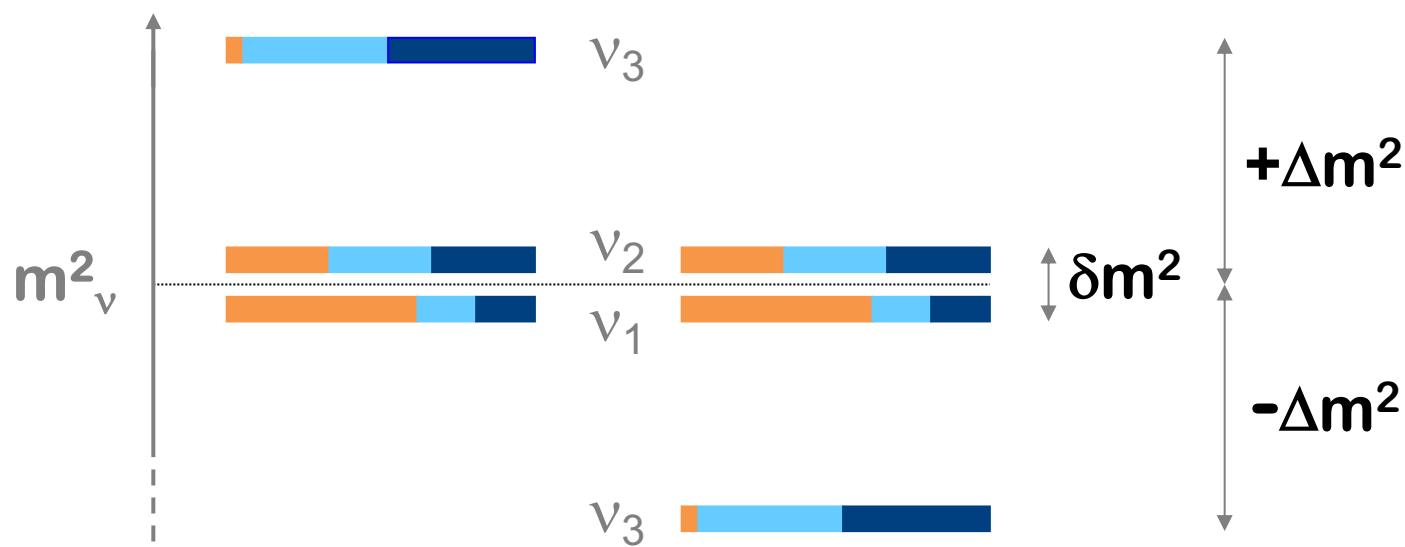
$$\begin{aligned}\delta m^2 &\sim 8 \times 10^{-5} \text{ eV}^2 \\ \Delta m^2 &\sim 2 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \theta_{12} &\sim 0.3 \\ \sin^2 \theta_{23} &\sim 0.5 \\ \sin^2 \theta_{13} &\sim 0.02\end{aligned}$$

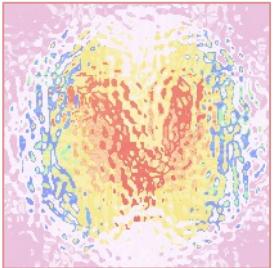


5 unknowns:

δ CPV Dirac phase
sign(Δm^2) → NO/IO
 θ_{23} octant degeneracy
absolute mass scale
Dirac/Majorana nature

Normal Ordering (NO) $e \mu \tau$ Inverted Ordering (IO)





From sketch to
accurate maps:
combine inform.
from all ν data



Useful to analyze oscillation data in the following sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param. δm^2 , Δm^2 , θ_{13} , θ_{23} , θ_{12} , δ , NO/IO

LBL Accel + Solar + KL + SBL Reactor

add sensitivity to Δm^2 , θ_{13} and affect **other parameters** via correlations

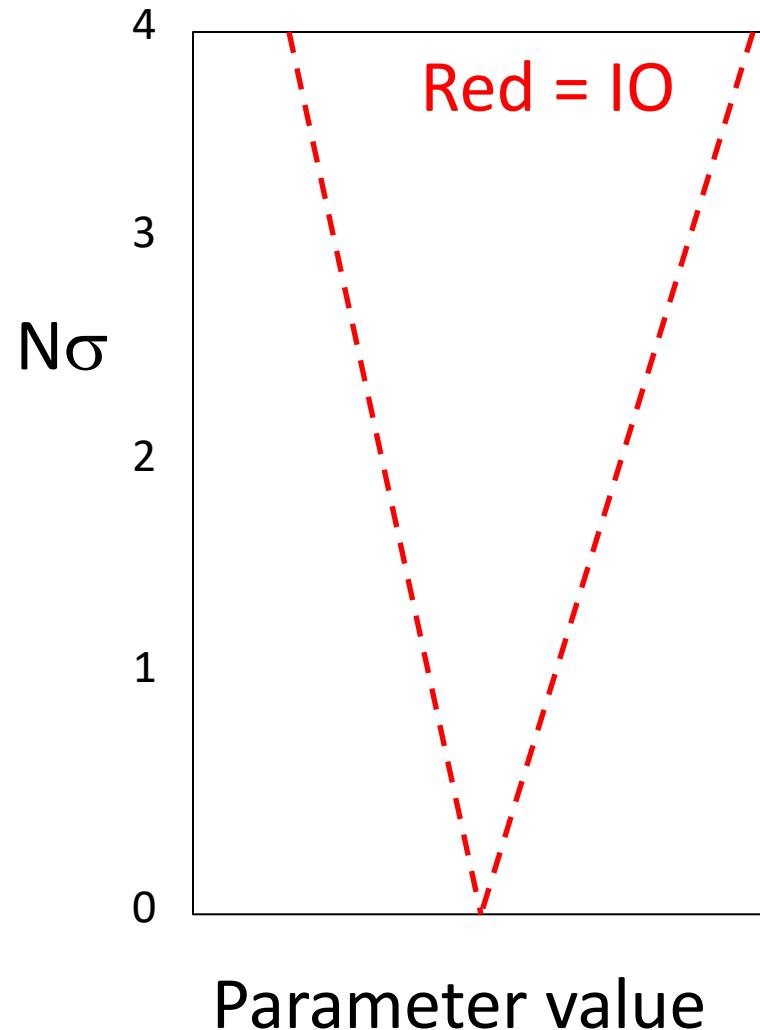
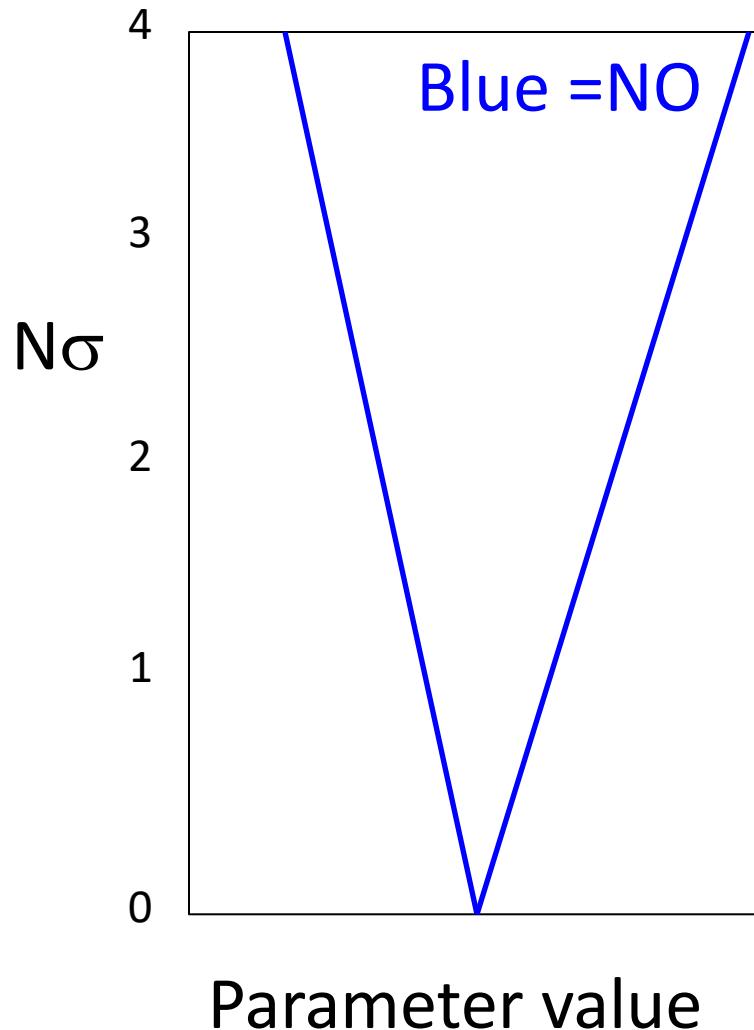
LBL Accel + Solar + KL + SBL Reactor + Atmosph.

add sensitivity to Δm^2 , θ_{23} , δ , NO/IO (but: entangled information in atmos.)

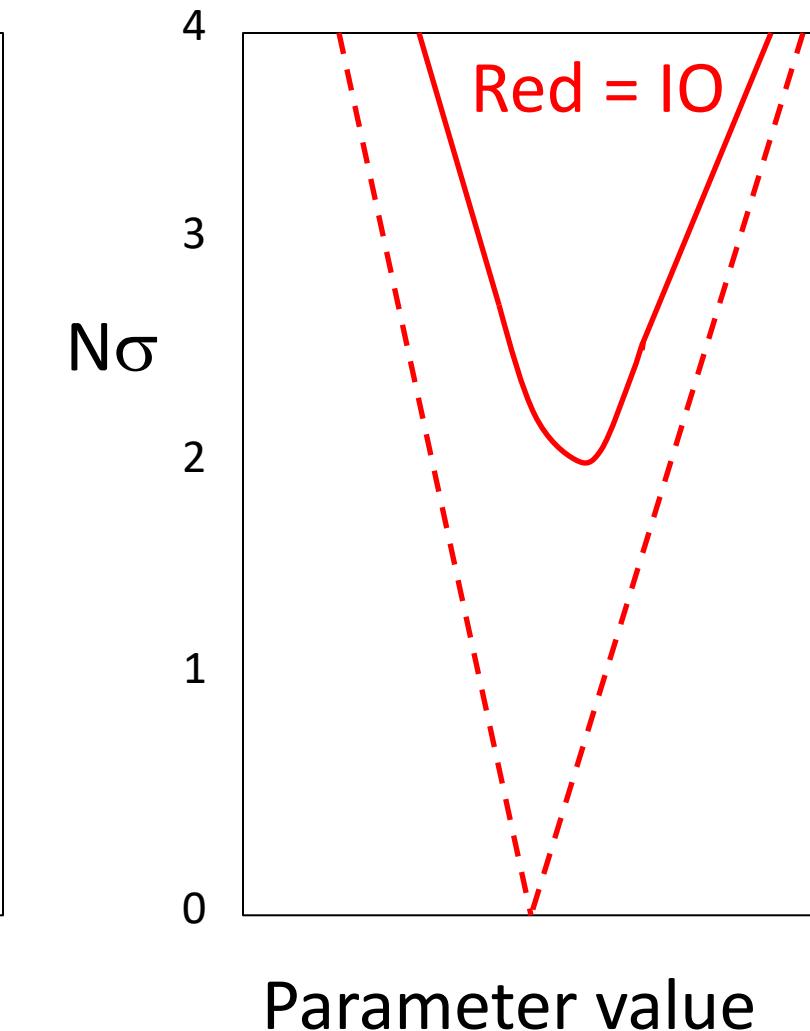
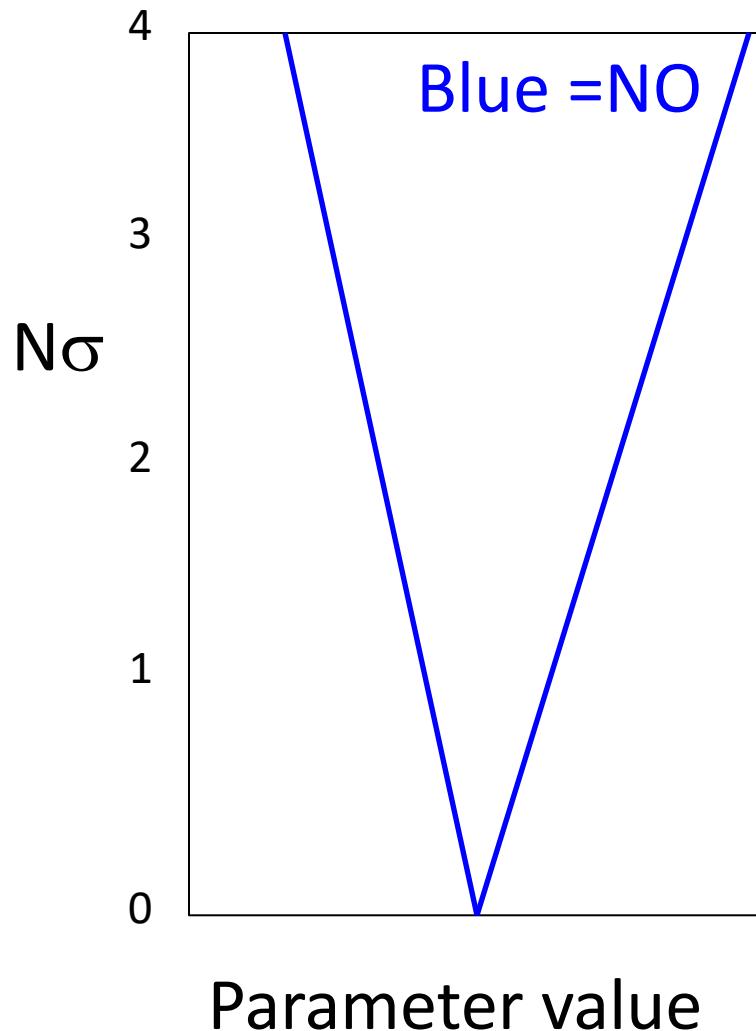
Results from Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo:

hep-ph 2107.00532

Parameter bounds at $N\sigma = \sqrt{\Delta\chi^2}$ would scale linearly
in the limit of \sim gaussian errors around best fits



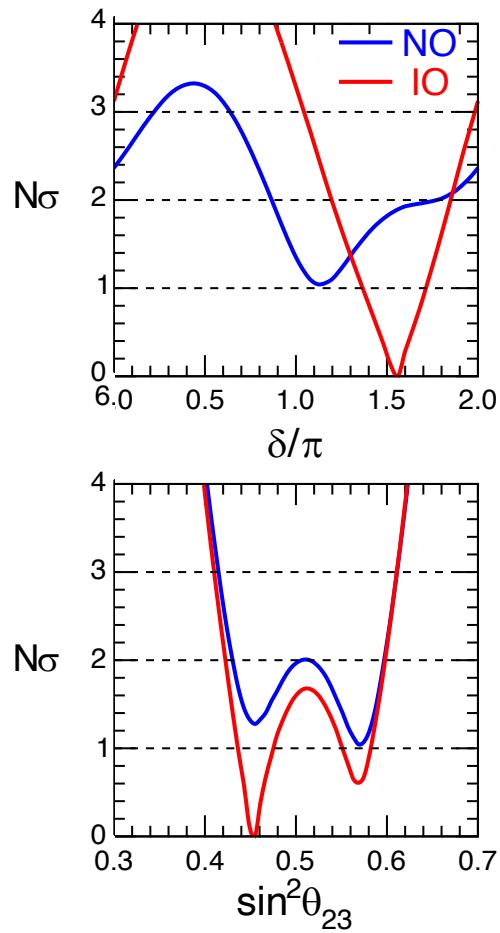
Bounds for one given mass ordering move upwards,
if the other mass ordering is preferred, e.g.:



Results →

Focus on the three oscillation unknowns: NO/IO, δ , θ_{23} octant degen.

LBL Acc + Solar + KamLAND



IO favored ($\sim 1\sigma$)

$\delta \sim 1.5\pi$ (IO), $\sim \pi$ (NO)

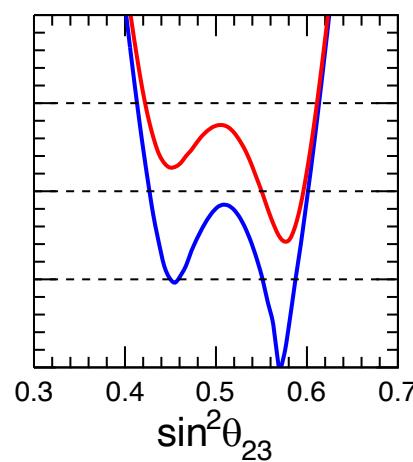
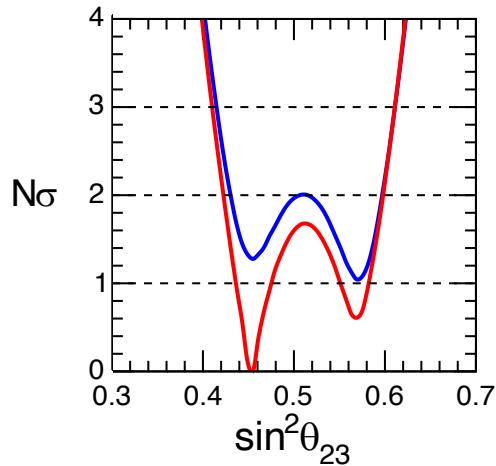
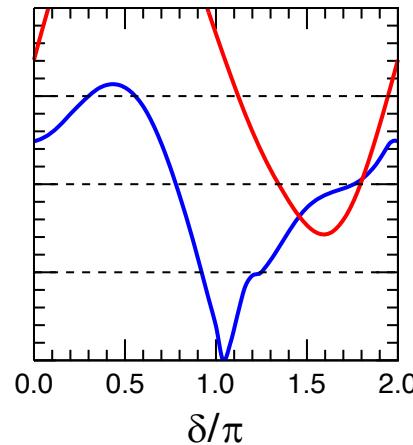
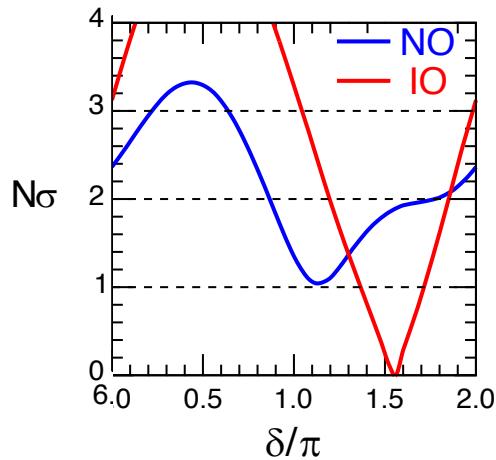
θ_{23} octants ~degenerate

Focus on the three oscillation unknowns: NO/IO, δ , θ_{23} octant degen.

LBL Acc + Solar + KamLAND



+ SBL Reactors



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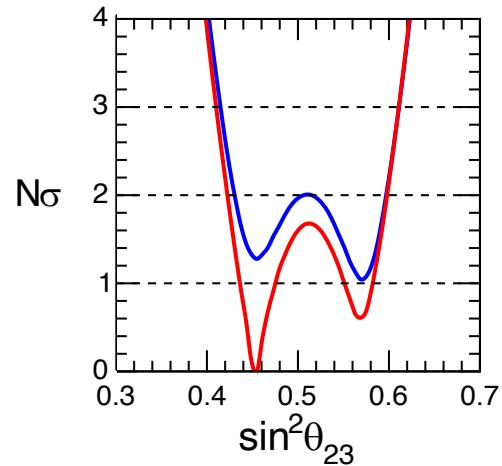
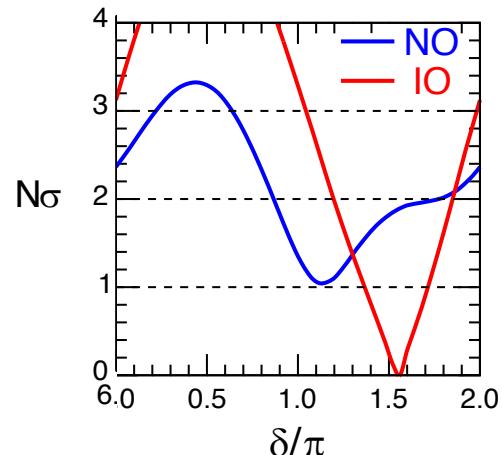
NO favored ($\sim 1.5\sigma$)

$\delta \sim \pi$ (NO), $\sim 1.5\pi$ (IO)

$\theta_{23} \sim 0.57$ favored ($\sim 1\sigma$)

Focus on the three oscillation unknowns: NO/IO, δ , θ_{23} octant degen.

LBL Acc + Solar + KamLAND

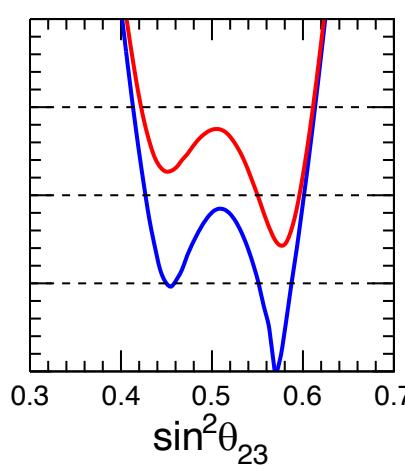
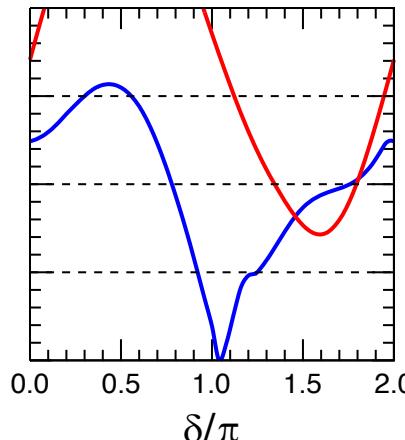


IO favored ($\sim 1\sigma$)

$\delta \sim 1.5\pi$ (IO), $\sim \pi$ (NO)

θ_{23} octants ~degenerate

+ SBL Reactors

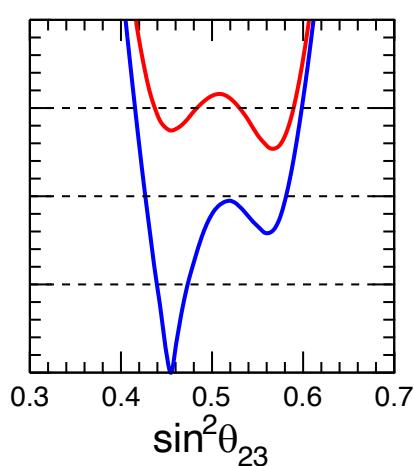
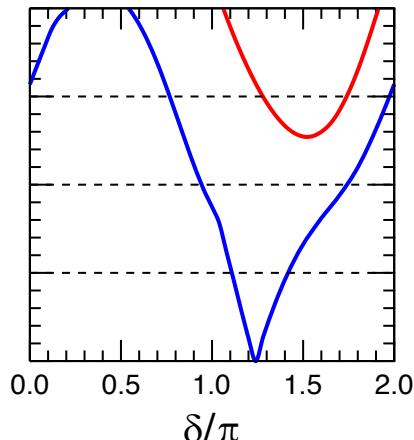


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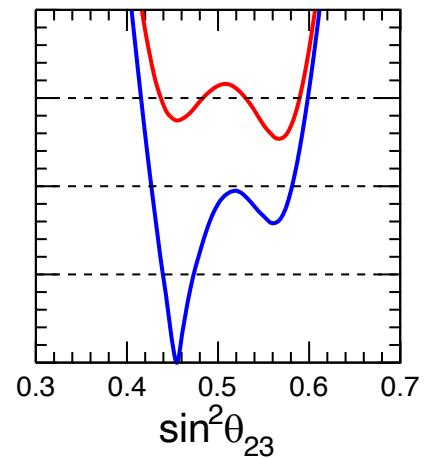
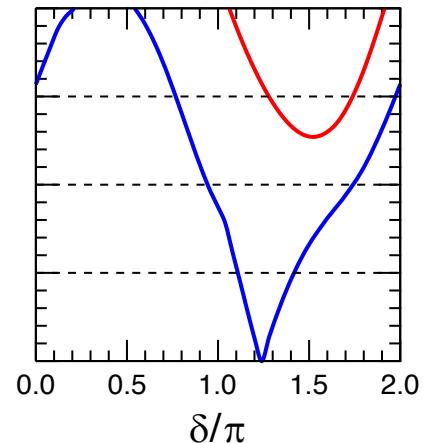
+ Atmos



NO favored ($\sim 2.5\sigma$)

$\delta \sim 1.2\pi$ (NO) fav. ($\sim 1.6\sigma$)

$\theta_{23} \sim 0.46$ favored ($\sim 1.6\sigma$)



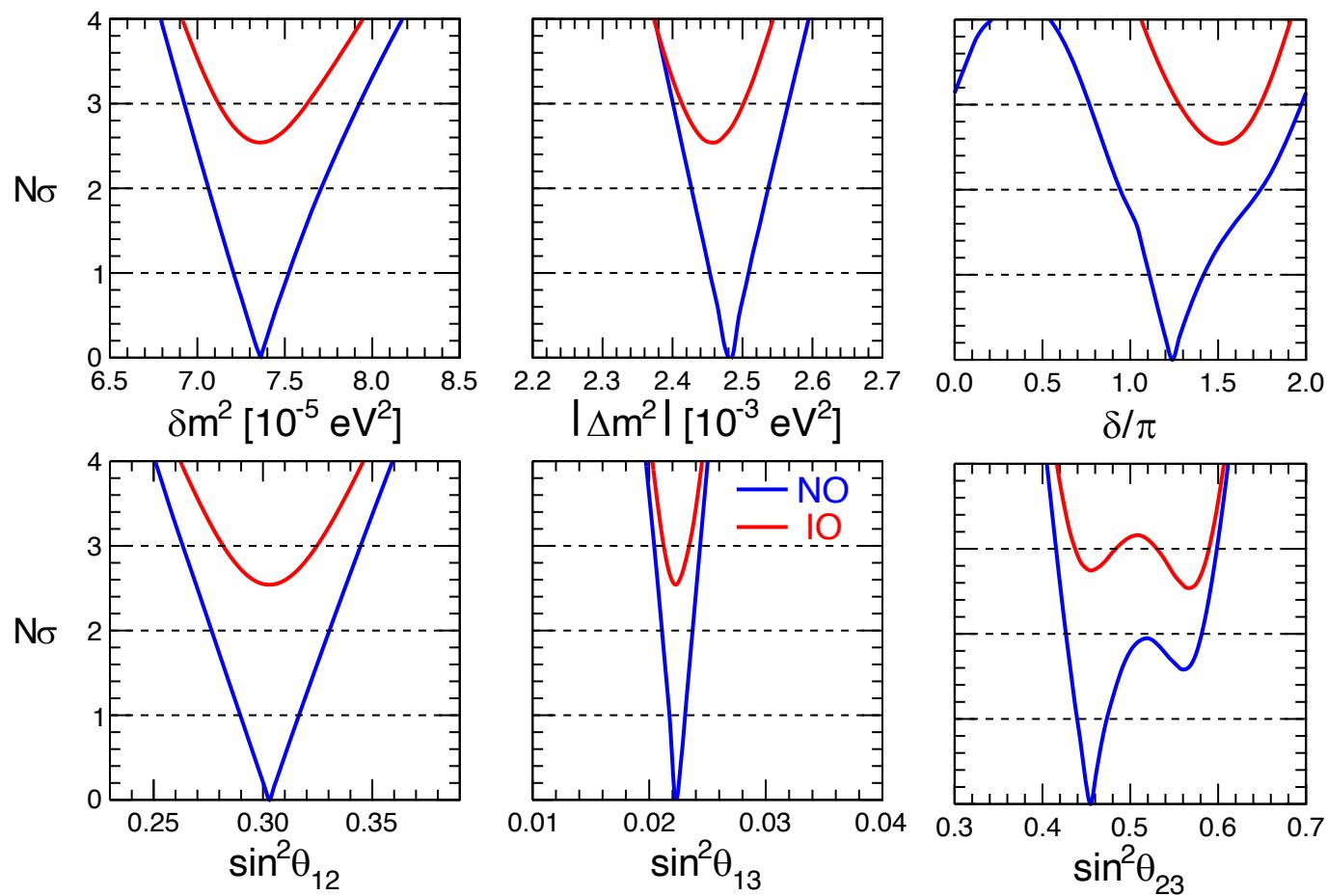
Hints on oscillation
unknowns
(+ personal rating...)

NO $\sin\delta < 0$ $\theta_{23} < \pi/4$	$\sim 99\% \text{ CL}$ *** $\sim 90\% \text{ CL}$ ** $\sim 90\% \text{ CL}$ *
--	---

Summary of known and unknown 3ν oscillation parameters, circa 2021

1σ error of known parameters

$ \Delta m^2 $	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%



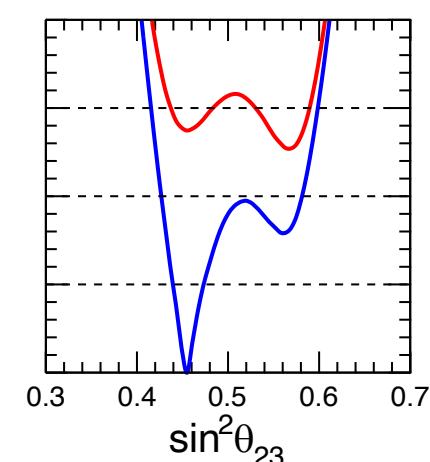
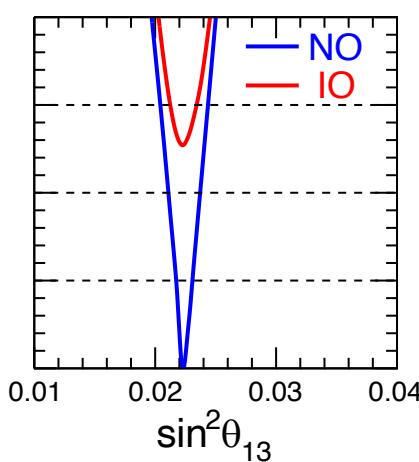
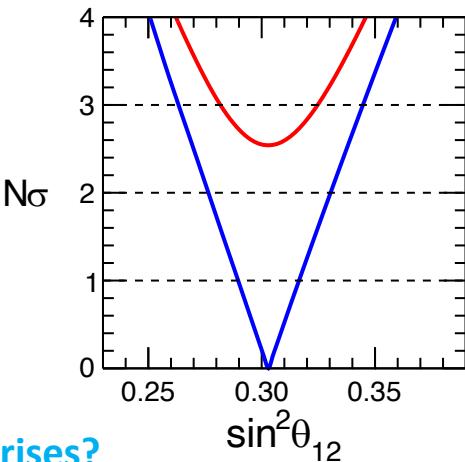
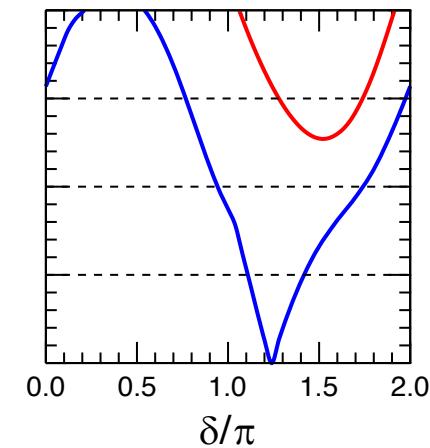
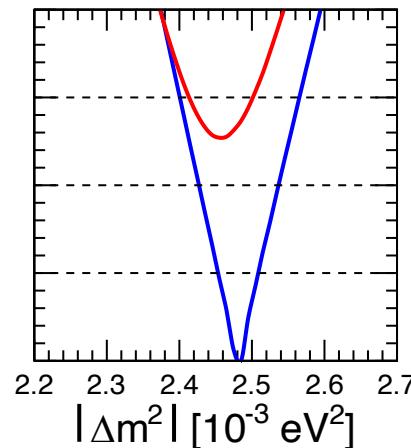
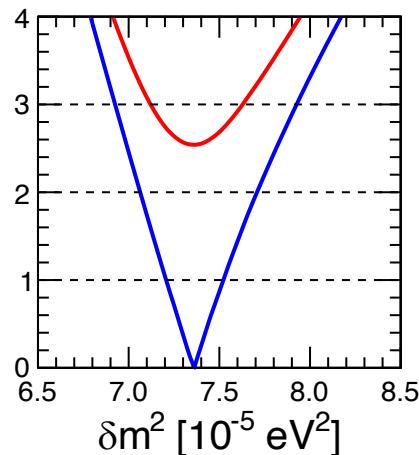
Hints on oscillation unknowns

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$\theta_{23} < \pi/4$	$\sim 90\% \text{ CL}$

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PRECISION

+surprises?

Progress expected on all fronts except for θ_{13} (difficult to improve)

DISCOVERY

Hints on oscillation unknowns

NO	$\sim 99\% \text{ CL}$
$\sin \delta < 0$	$\sim 90\% \text{ CL}$
$\theta_{23} < \pi/4$	$\sim 90\% \text{ CL}$

Selected questions from current (un)knowns:

- Q1:** Why adding SBL reactors flips preference from IO to NO, if these oscill. data are not sensitive to mass ordering?
- Q2:** δ , NO/IO, θ_{23} octant are all entangled in $\nu_\mu \rightarrow \nu_e$ oscillations. What are LBL accel. expts telling us in this channel?
- Q3:** Can we really be confident about ~1% accuracy on Δm^2 ?

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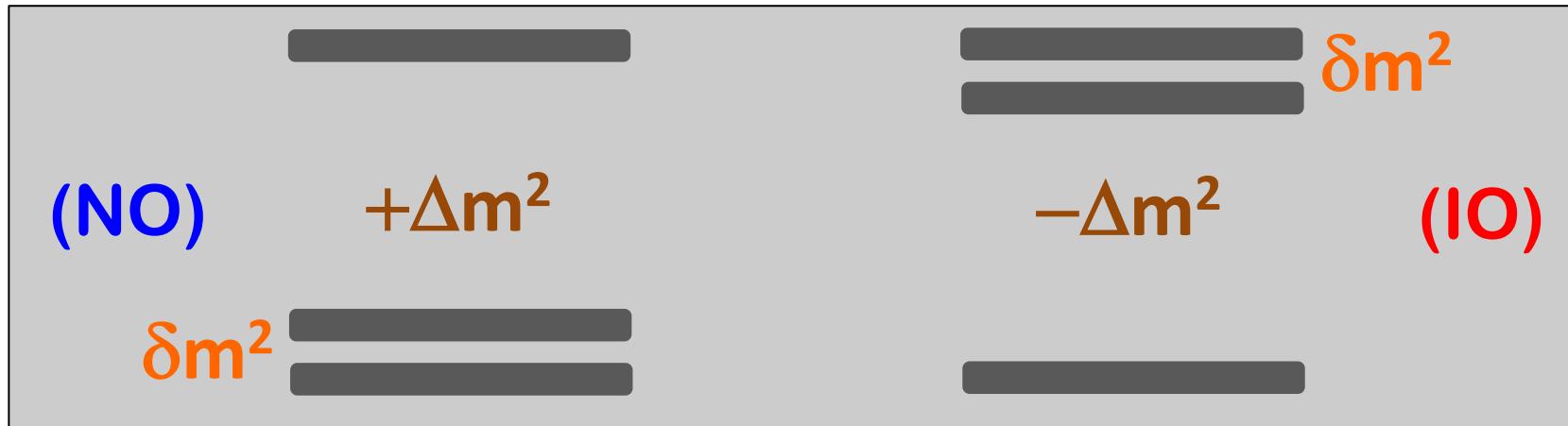
Q3: Can we really be confident about ~1% accuracy on Δm^2 ?

Answers (will) rely upon integration of different sources of info:

Covariance of oscillation parameters
Complementarity of different expts
Collaboration among expt & theo

... key to future progress!

How do oscillation searches probe mass ordering?



Observe **interference effects** of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with known sign. Options:

$Q \sim \delta m^2$ (medium-baseline reactors → JUNO)

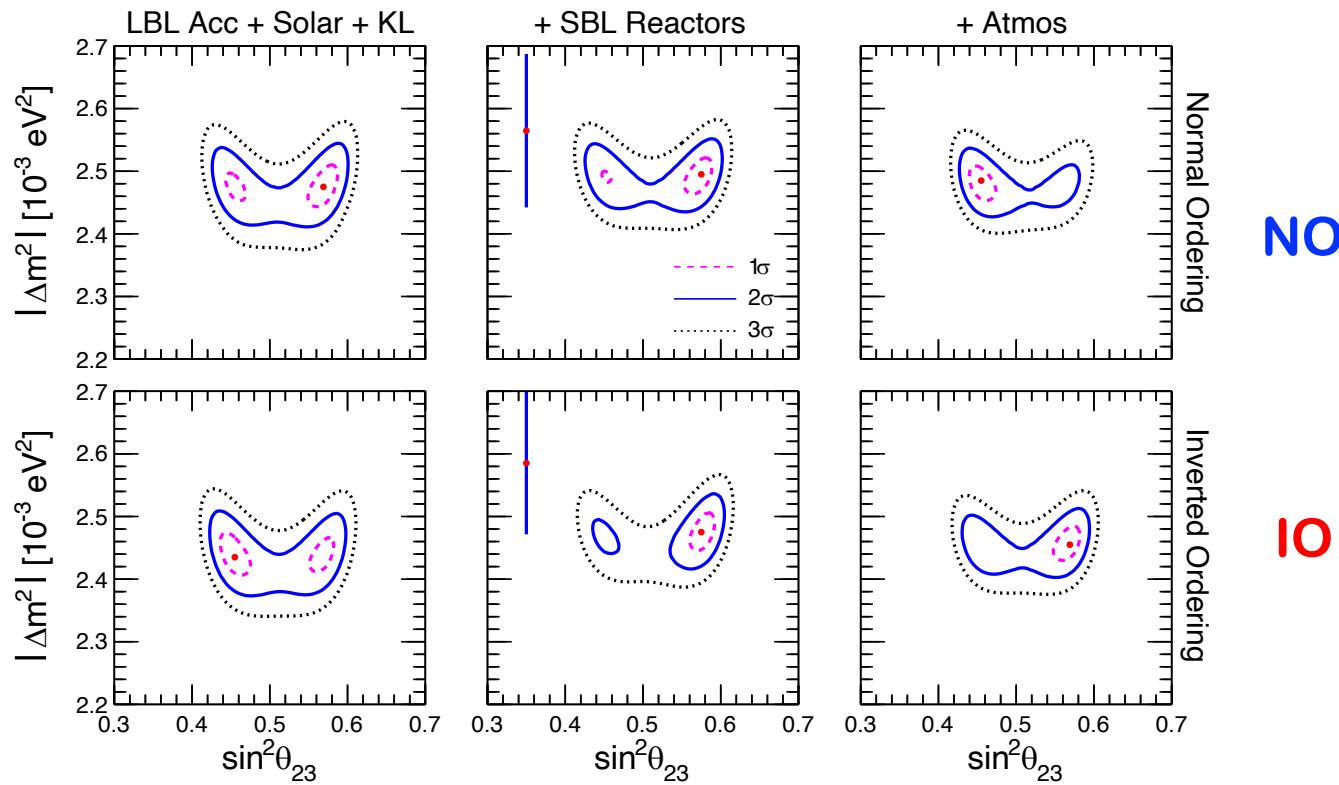
$Q \sim G_F N_e E$ (ν -matter effects → atm & LBL accel. expt.)

$Q \sim G_F N_\nu E$ ($\nu-\nu$ collective effects → SN, difficult!)

Additional handle: complementarity of different Δm^2 data in NO/IO →

$(\pm\Delta m^2, \theta_{23})$ covariance & complementarity of experiments

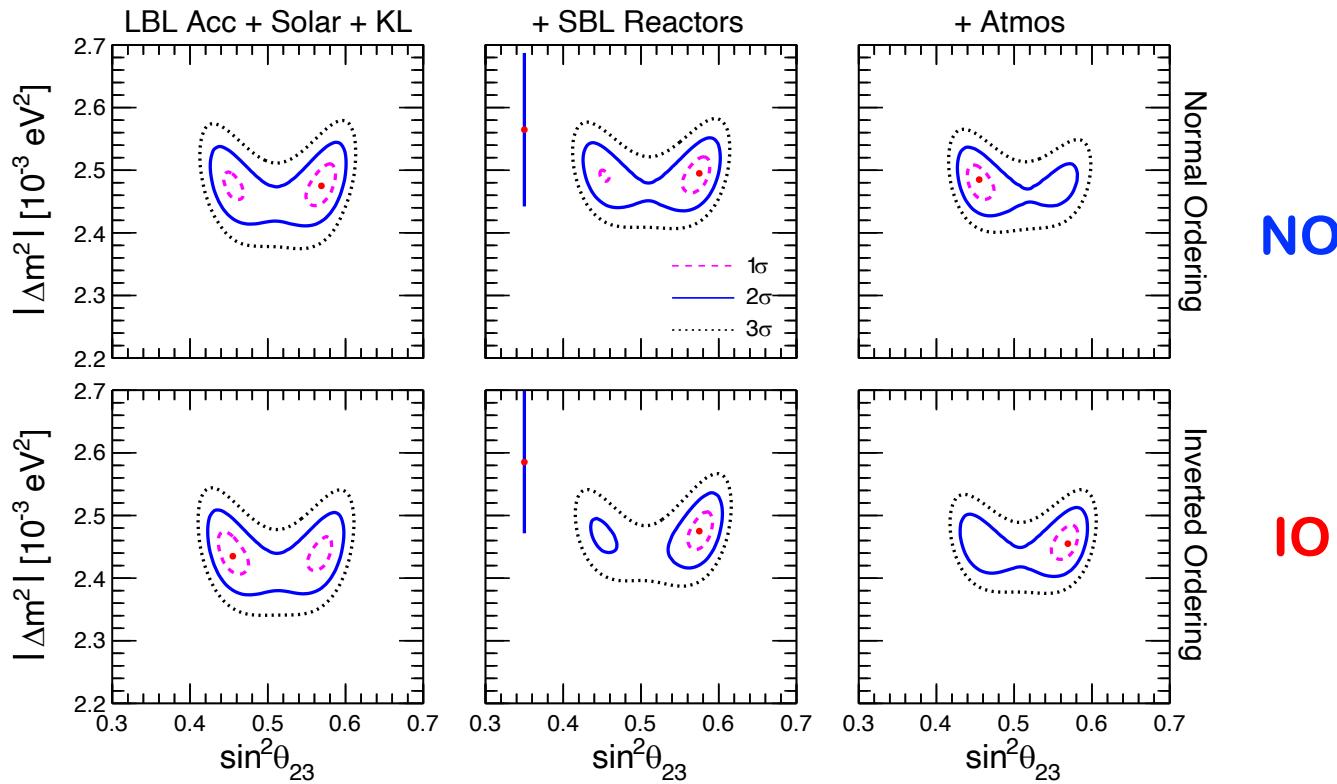
Standalone
SBL reactor
data, 2021



Q1: Why adding SBL reactors flips preference from IO to NO,
if these oscill. data are not sensitive to mass ordering?

$(\pm\Delta m^2, \theta_{23})$ covariance & complementarity of experiments

Standalone
SBL reactor
data, 2021



A1. SBL reactors prefer higher Δm^2 than LBL accel. (and atmos.) expts.

Relative difference is smaller for NO and for non-maximal θ_{23} mixing

→ Better convergence reached for NO, nonmax θ_{23} , intermediate Δm^2

Future: probe NO/IO by complementary Δm^2 data (e.g. JUNO+ORCA)

How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?

CPV is a genuine 3ν effect. For two neutrinos, no CPV:

$$\stackrel{(-)}{\nu}_e = \cos\theta_{12} \nu_1 + \sin\theta_{12} \nu_2$$

For three neutrinos: new possible CPV phase δ , tested via $\nu / \bar{\nu}$

$$\stackrel{(-)}{\nu}_e = \cos\theta_{13} (\cos\theta_{12} \nu_1 + \sin\theta_{12} \nu_2) + e^{\pm i\delta} \sin\theta_{13} \nu_3$$



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PHYSICS LETTERS

2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*

*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation. CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal. Time reversal invariance requires the oscillation probability to be an even function of time. Both conditions can be violated, even drastically, if more than two neutrinos exist.

[CP-odd matter bkgd in LBL accel. helps for NO/IO... but is a “nuisance” in this context]

Q2: δ , NO/IO, θ_{23} octant are all entangled in $\nu_\mu \rightarrow \nu_e$ oscillations.
What are LBL accel. expts telling us in this channel?

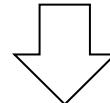
T2K vs NOvA tension, blurring current hints for NO and CPV

→ some details on bi-event plots (ν_e vs $\bar{\nu}_e$ events)

Q2: δ , NO/IO, θ_{23} octant are all entangled in $\nu_\mu \rightarrow \nu_e$ oscillations.
What are LBL accel. expts telling us in this channel?

T2K vs NOvA “tension”, blurring current hints for NO and CPV

→ some details on bi-event plots (ν_e vs $\bar{\nu}_e$ events)

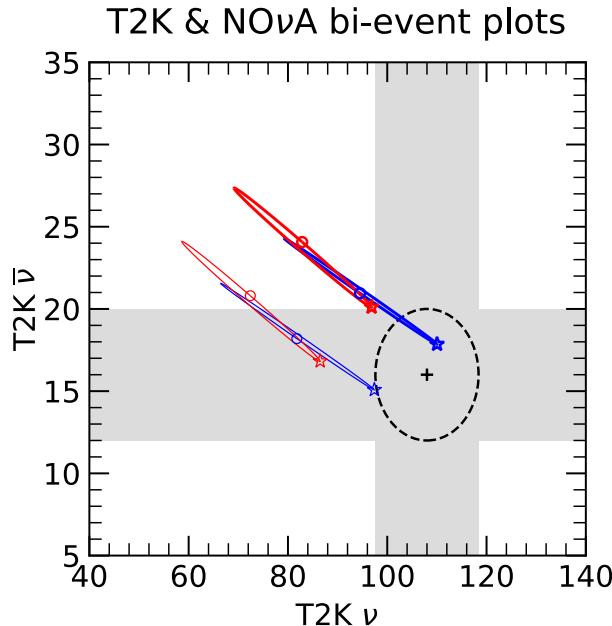


Speculations on a possible role of ν interaction uncertainties

→ general comments on EW nuclear physics

Q3: Can we really be confident about ~1% accuracy on Δm^2 ?

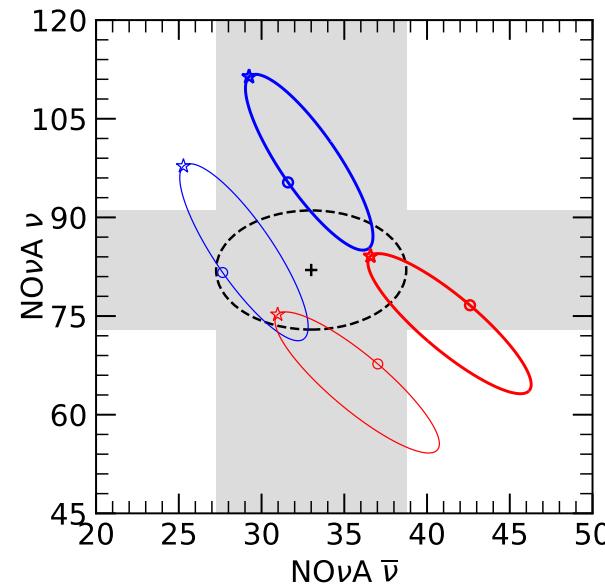
Integrated info on ν and $\bar{\nu}$, stat. errors only. [Not used in fits]



$$s_{23}^2 = \frac{0.57}{0.45} \quad \text{NO} \quad \text{IO} \quad \delta = \frac{\pi}{3\pi/2} \quad \star$$

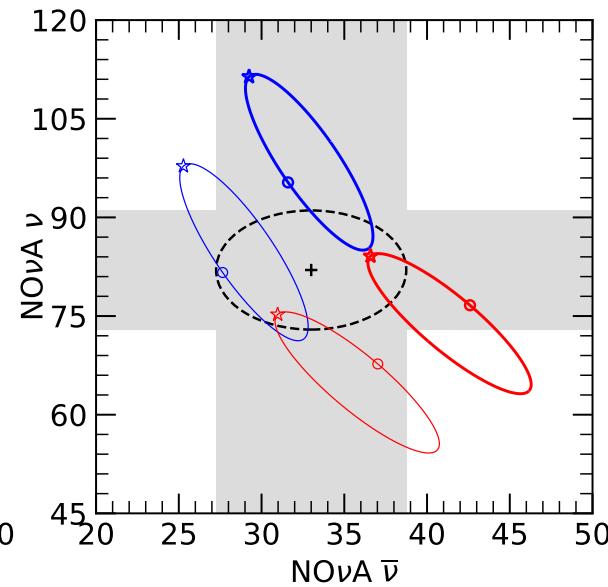
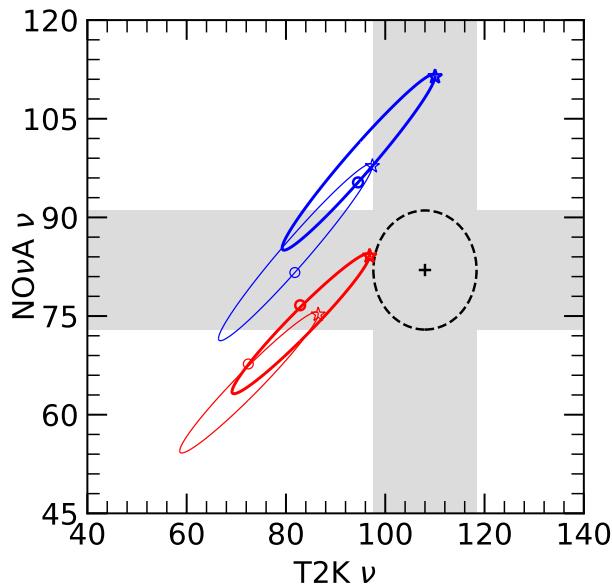
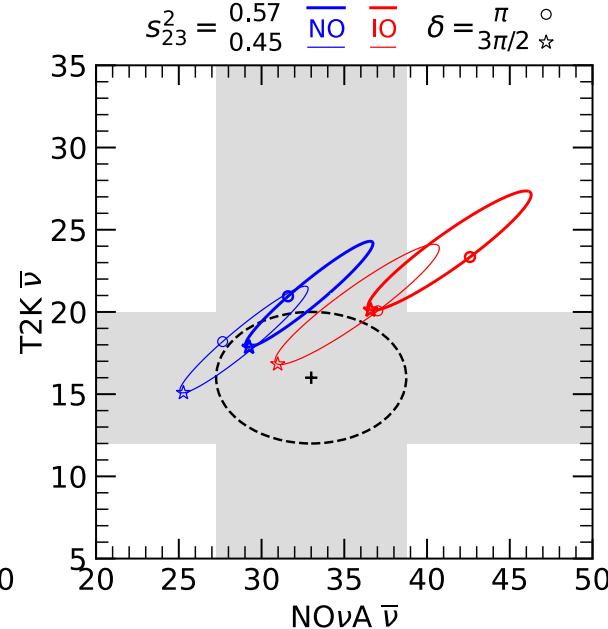
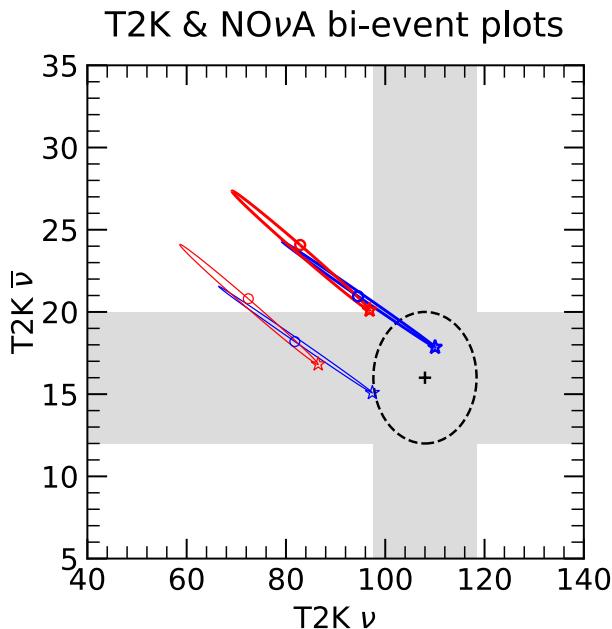
T2K ($\nu+\bar{\nu}$) prefers:
NO
 $\delta \sim 3\pi/2$ (~max CPV)
2nd octant

NOVA ($\nu+\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate



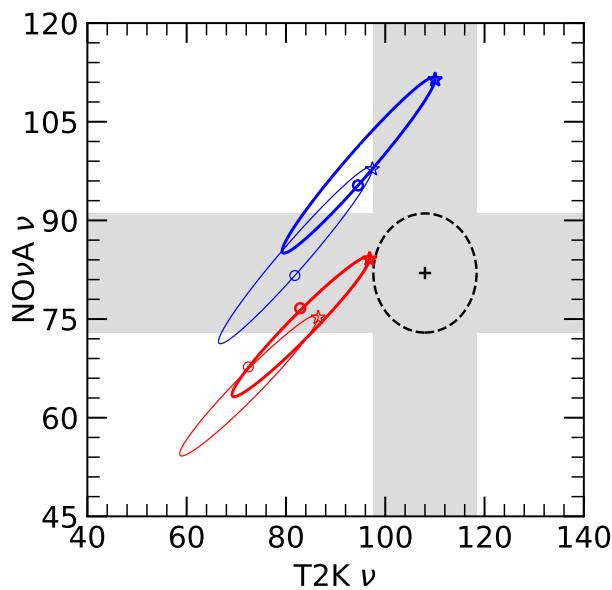
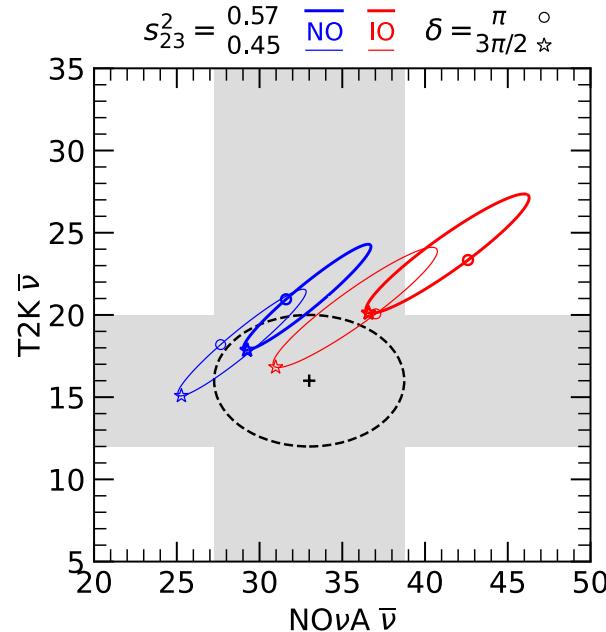
→ T2K and NOVA, separately: **NO preferred; CP and octant ambiguous**

The same info can be reorganized in terms of T2K vs NO ν A:



T2K & NO ν A bi-event plots

T2K+NO ν A (ν) prefer:
 IO
 $\delta \sim 3\pi/2$
 1st octant



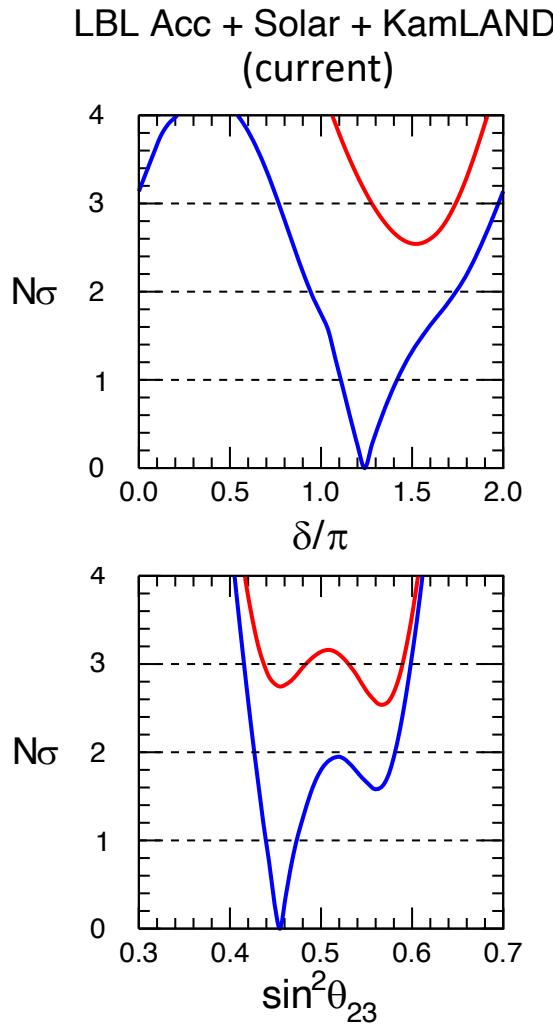
T2K+NO ν A ($\bar{\nu}$) prefer:
 IO
 $\delta \sim 3\pi/2$
 2nd octant

→ T2K and NOVA, jointly: **IO and CPV preferred; octant ambiguous**

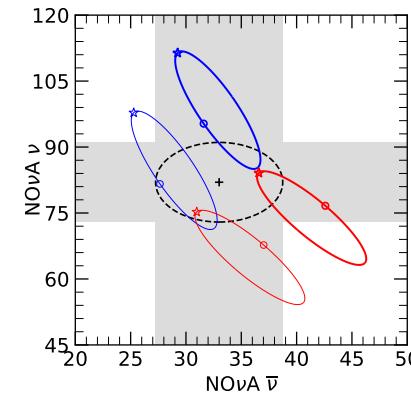
...In the T2K+NOvA combination, still unstable results on three unknowns:

mass ordering (NO vs IO), θ_{23} octant and CP phase δ

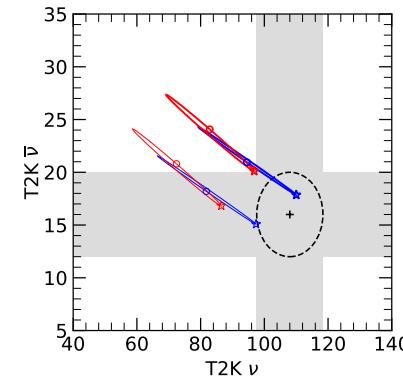
Further data may tilt the current balance, or even point to new physics (NSI?)



NOvA close to different options within 1σ ...



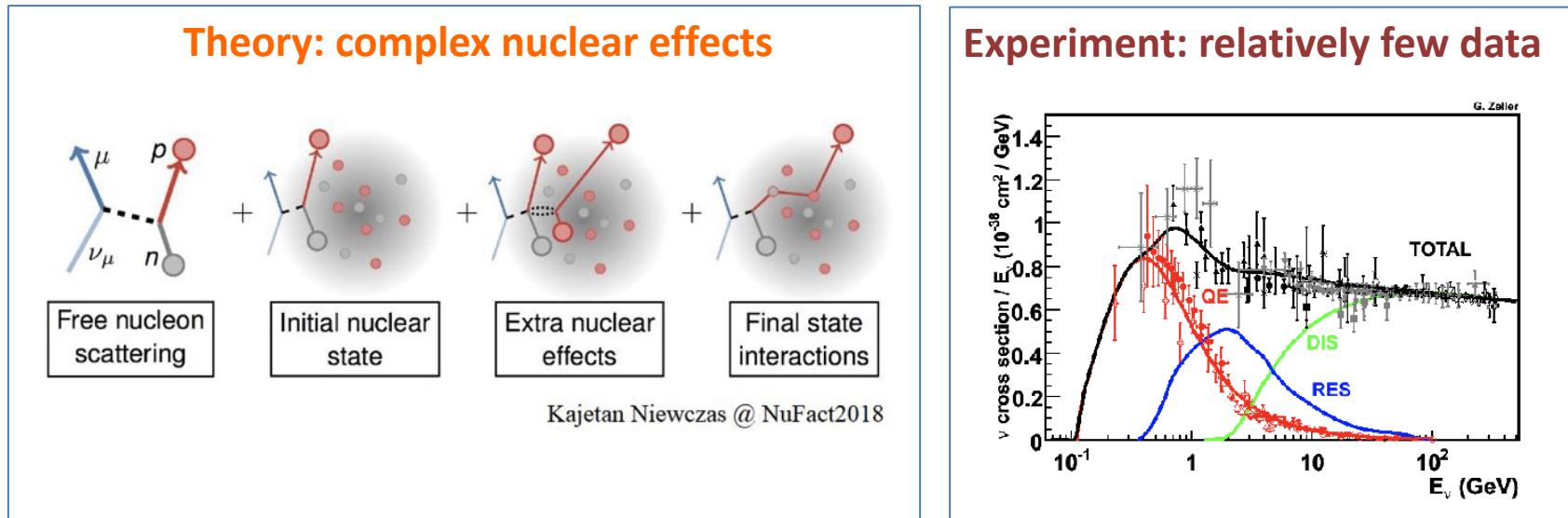
T2K close to the edge of its expected sensitivity...



T2K + NOvA Joint analysis?

In any case: Parameter covariances and data tensions show the delicate interplay between 2 knowns [Δm^2 , θ_{23}] and 3 unknowns [NO/IO, δ , sign ($\theta_{23} - \pi/4$)]

There is a general issue that affects all these (un)knowns:
neutrino interactions in nuclei are not known as accurately as desired!

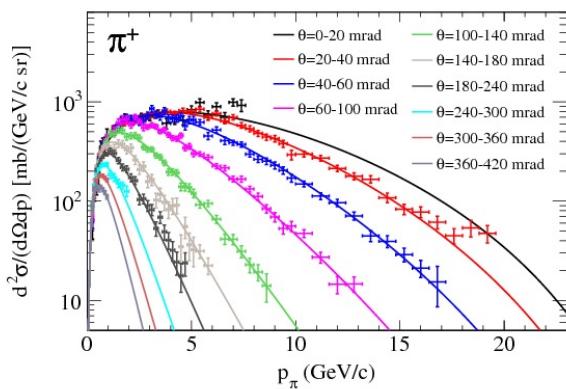


Great effort to improve the situation through dedicated (e.g. ND) experiments and improved nuclear models, but non-negligible uncertainties remain
→ May affect central values and errors of (un)known oscillation parameters

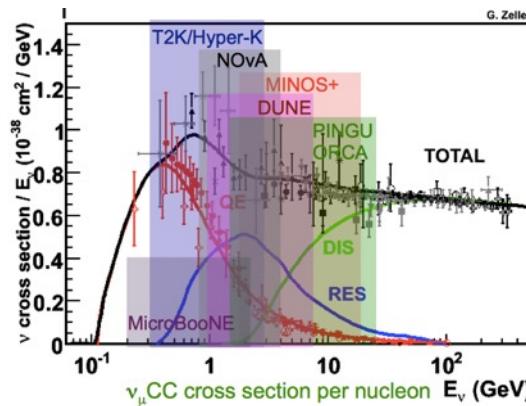
Current 1% global-fit formal accuracy on Δm^2 might be optimistic

“Strong interaction” effects on “weak interaction” physics are ubiquitous...

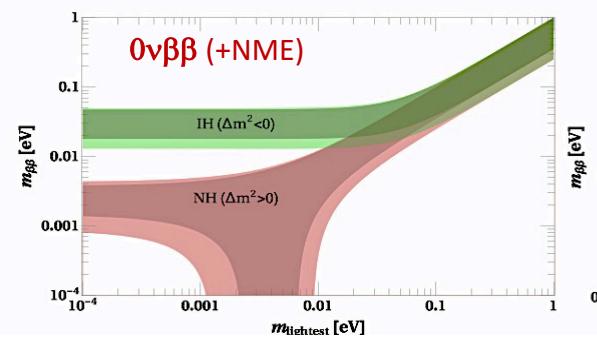
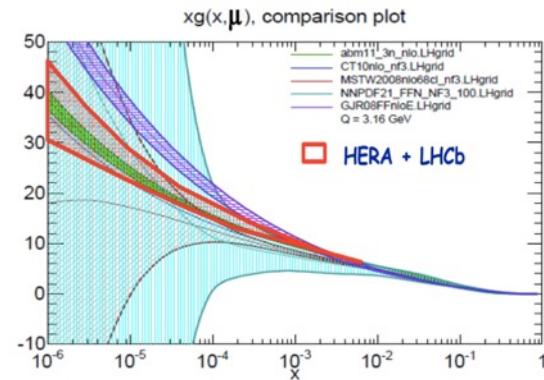
Need hadron production data, e.g. $pA \rightarrow \pi X$, +theory models to improve estimates of atm. and acceler. ν fluxes and errors



Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

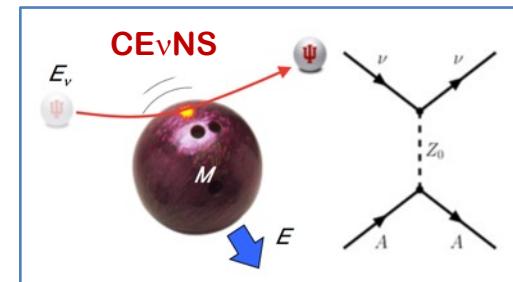


Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν



Control of nuclear EW response (e.g., form factors) relevant to interpret many low-energy data: 2β , coherent scatt., reactor spect.

...

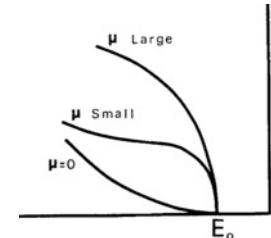


Progress requires further integration of different EXPT+THEO communities:
→ emerging field of “Electroweak Nuclear Physics”

Absolute neutrino mass and Dirac/Majorana nature: Integrating the last 3ν unknowns & their observables (m_β , $m_{\beta\beta}$, Σ)

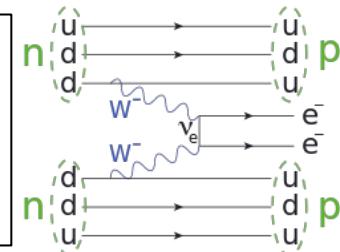
β decay, sensitive to the “effective electron neutrino mass”:

$$m_\beta = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{\frac{1}{2}}$$



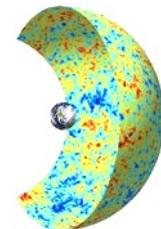
$0\nu\beta\beta$ decay: only if Majorana. “Effective Majorana mass”:

$$m_{\beta\beta} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$



Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$

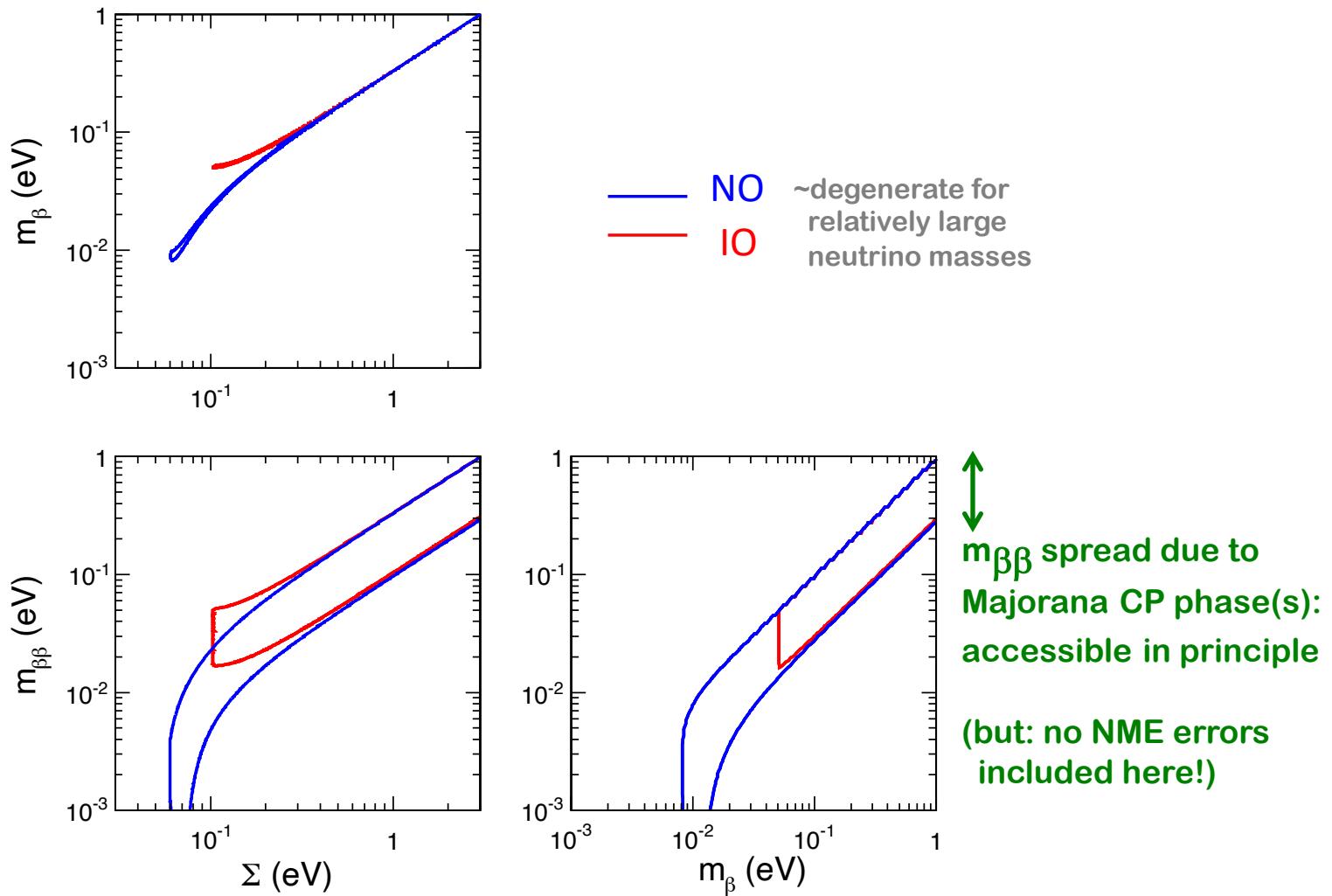


Note 1: These observables may provide handles to distinguish NO/IO.

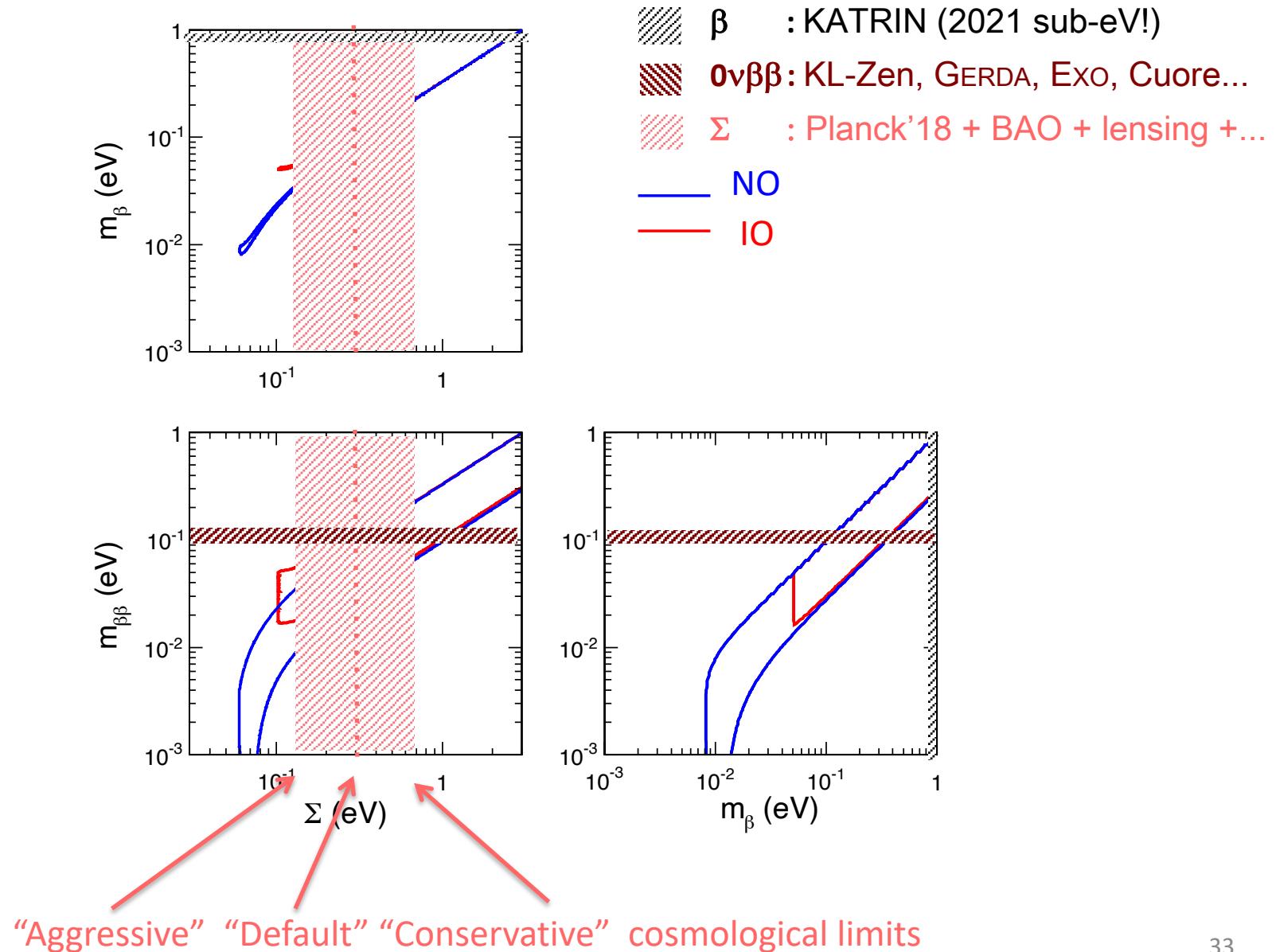
Note 2: Majorana case gives a new source of CPV (unconstrained)

Note 2: The three observables are correlated by oscillation data →

Impact of oscillations on non-oscillation parameter space

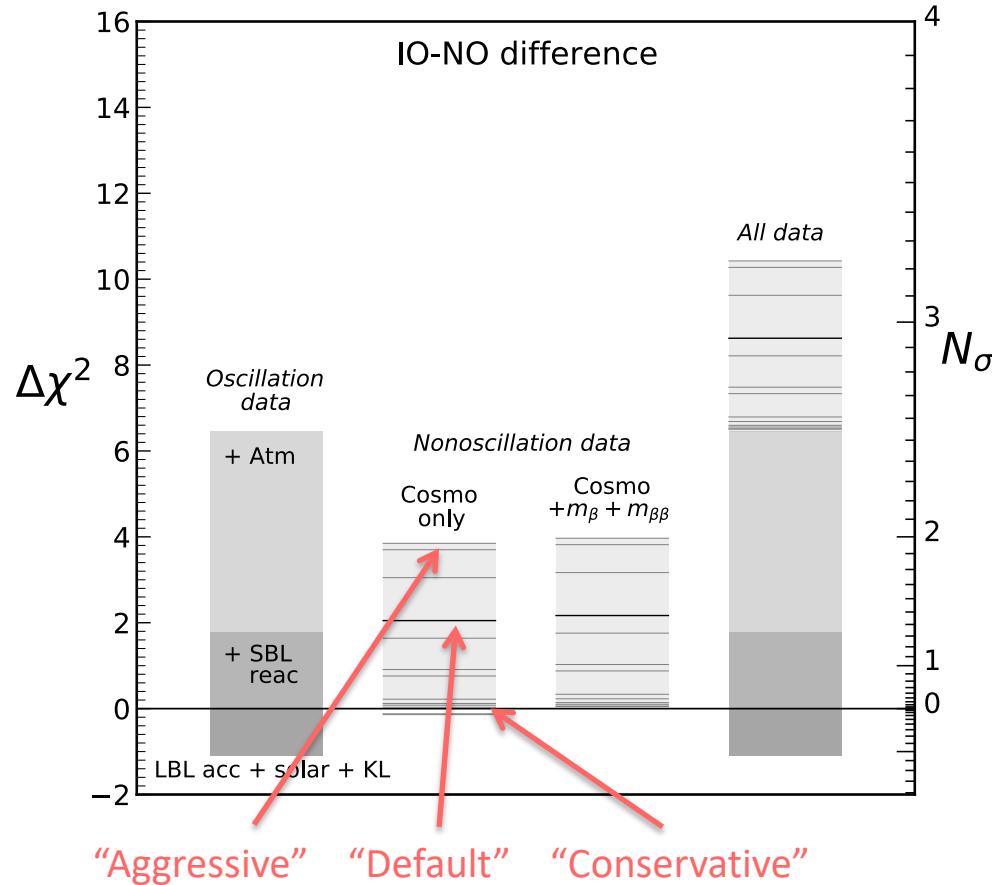


No signal (yet), but upper limits on m_β , $m_{\beta\beta}$, Σ (up to some syst.)



Impact of cosmology on IO-NO difference (global fit)

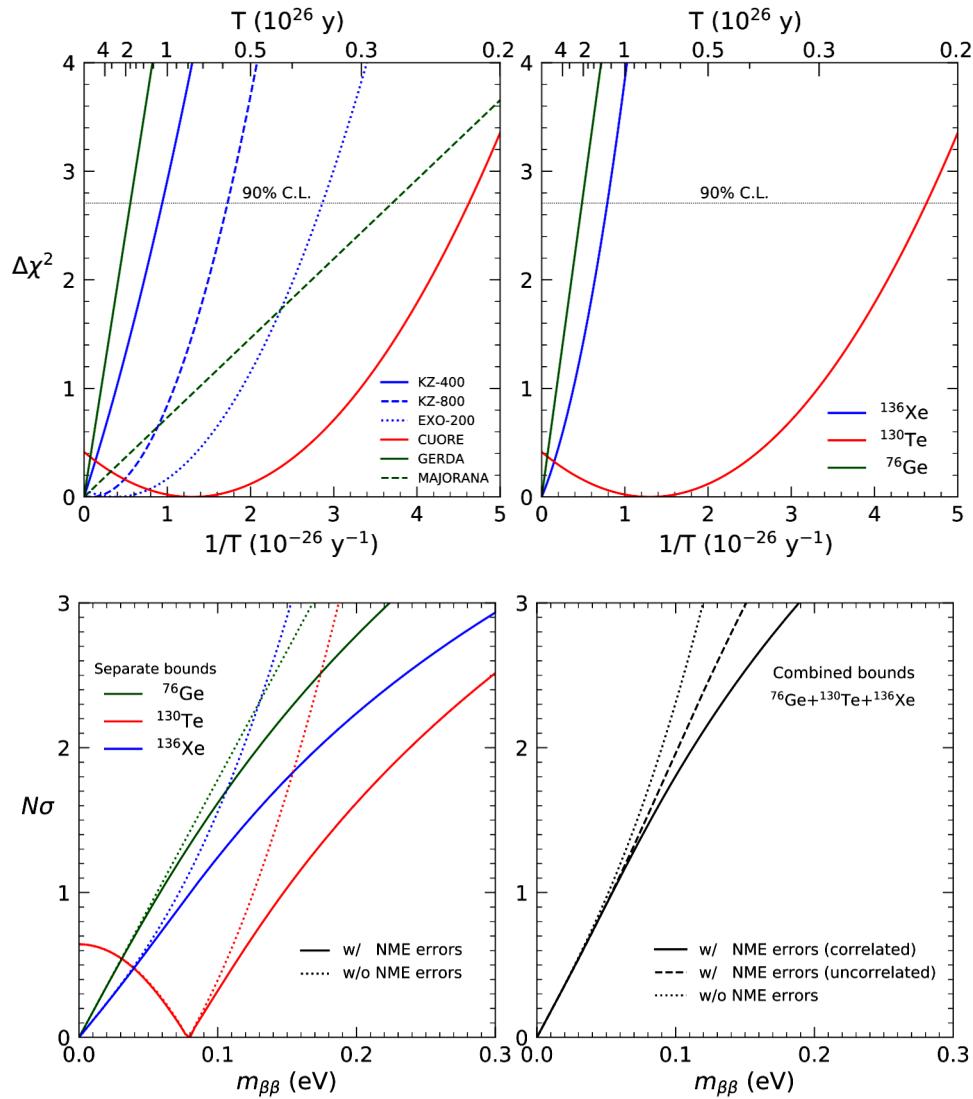
(envelope of conservative, default, aggressive cases = horizontal lines)



Cosmo data can add $\sim 0\text{--}0.7\sigma$ to the $\sim 2.5\sigma$ oscillation preference for NO

→ Global hint at $\sim 2.5\text{--}3.2 \sigma$ in favor of NO

Impact of $0\nu\beta\beta$ data still small, but combination interesting in itself:



Combination of data for the same nuclide possible if **likelihood of T or 1/T** is explicitly reported **by the experiments** (not just 90% CL limits)



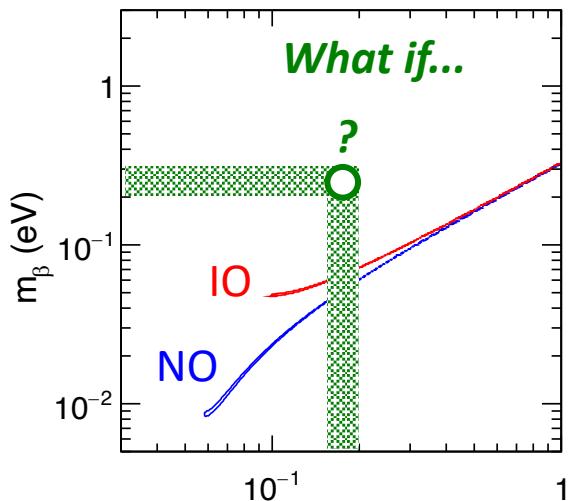
Combination of data for different nuclides possible if **correlated NME errors** are explicitly reported **by nuclear theorists** (not just NME ranges)



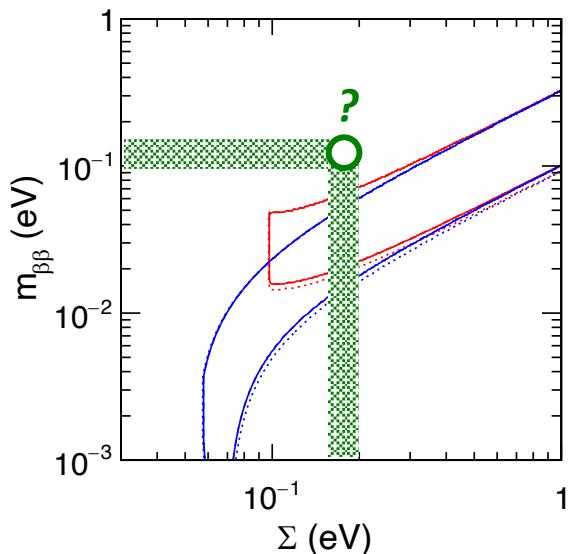
$m_{\beta\beta} < 0.11 \text{ eV } (2\sigma)$
our combination of data+NME

Future data might also bring us beyond 3 ν and re-shape the field!

Direct mass searches



Double beta decay



Lack of convergence among data
(barring expt mistakes) might point towards new possibilities:

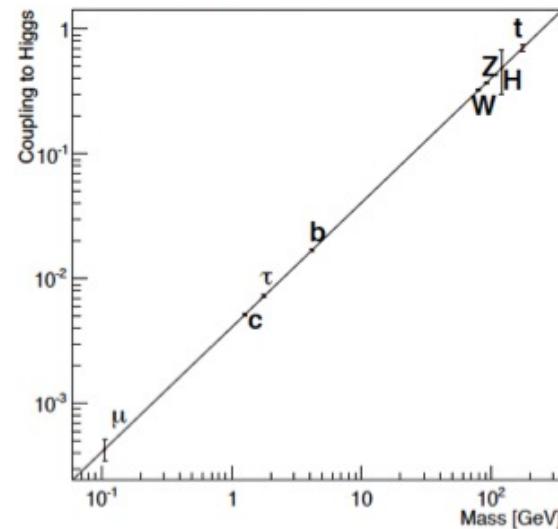
- Cosmology beyond Λ CDM
- Alternative DBD mechanisms
- New interactions (NSI)
- New neutrino states
- ...

Main contender in current ν physics:
Light sterile ν at O(eV) scale
... but confusing/unconfirmed hints

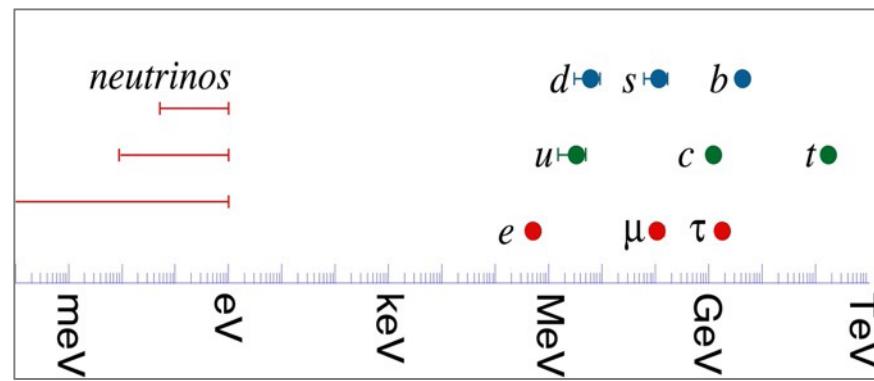
In any case: generic expectation for new sterile ν mass scale(s)

Particle masses: Linking two fundamental research programs

1. Test Higgs sector

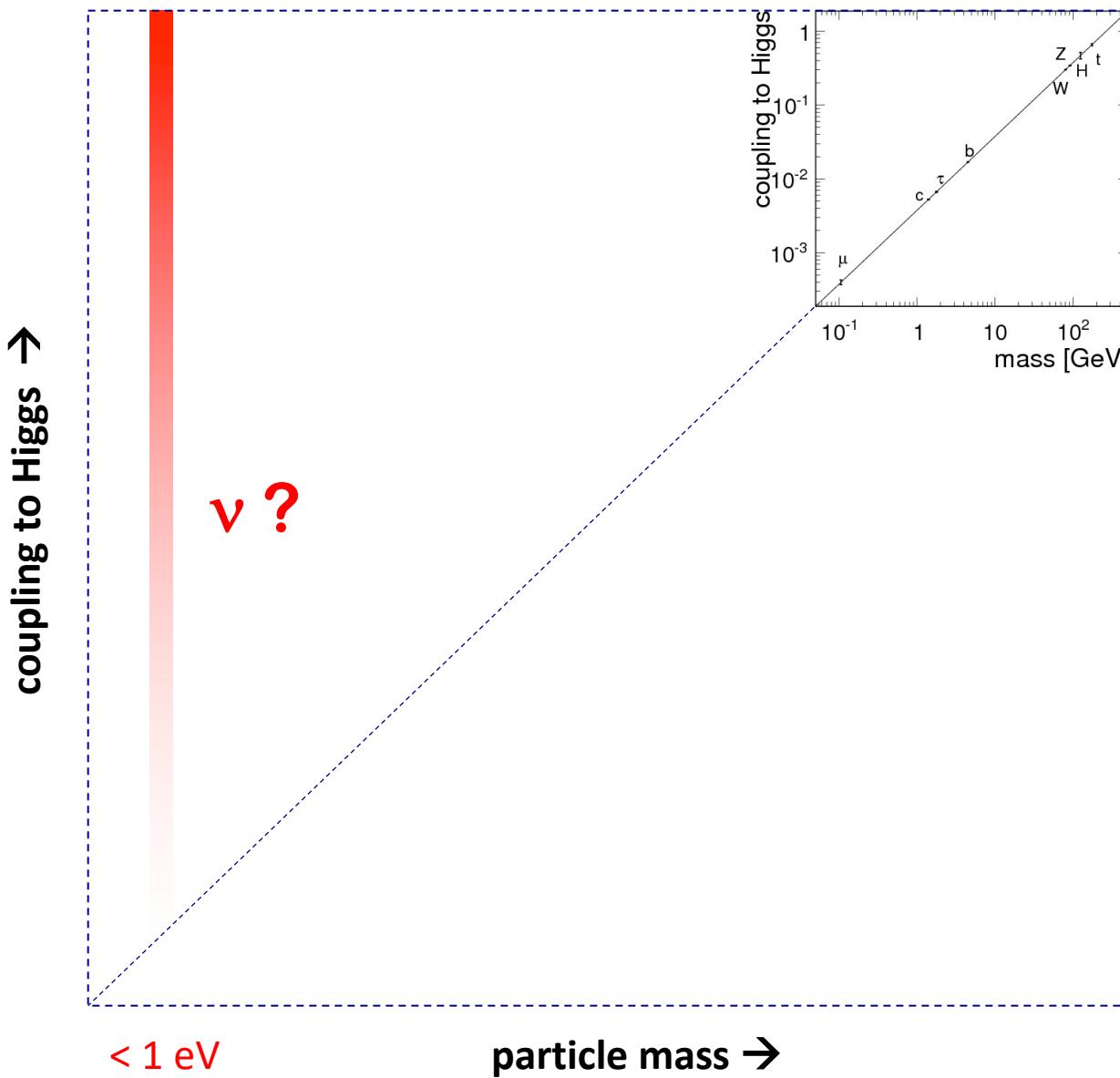


2. Find ν masses



1 + 2

Where are the ν 's on this plot? Why are they so light?



Options:

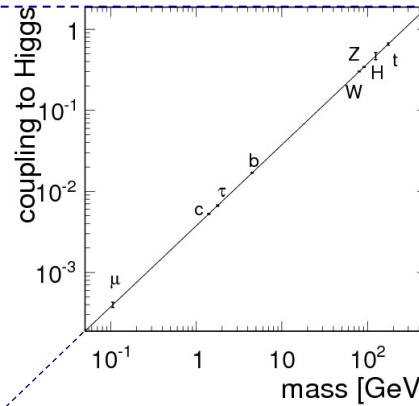
coupling to Higgs →

< 1 eV

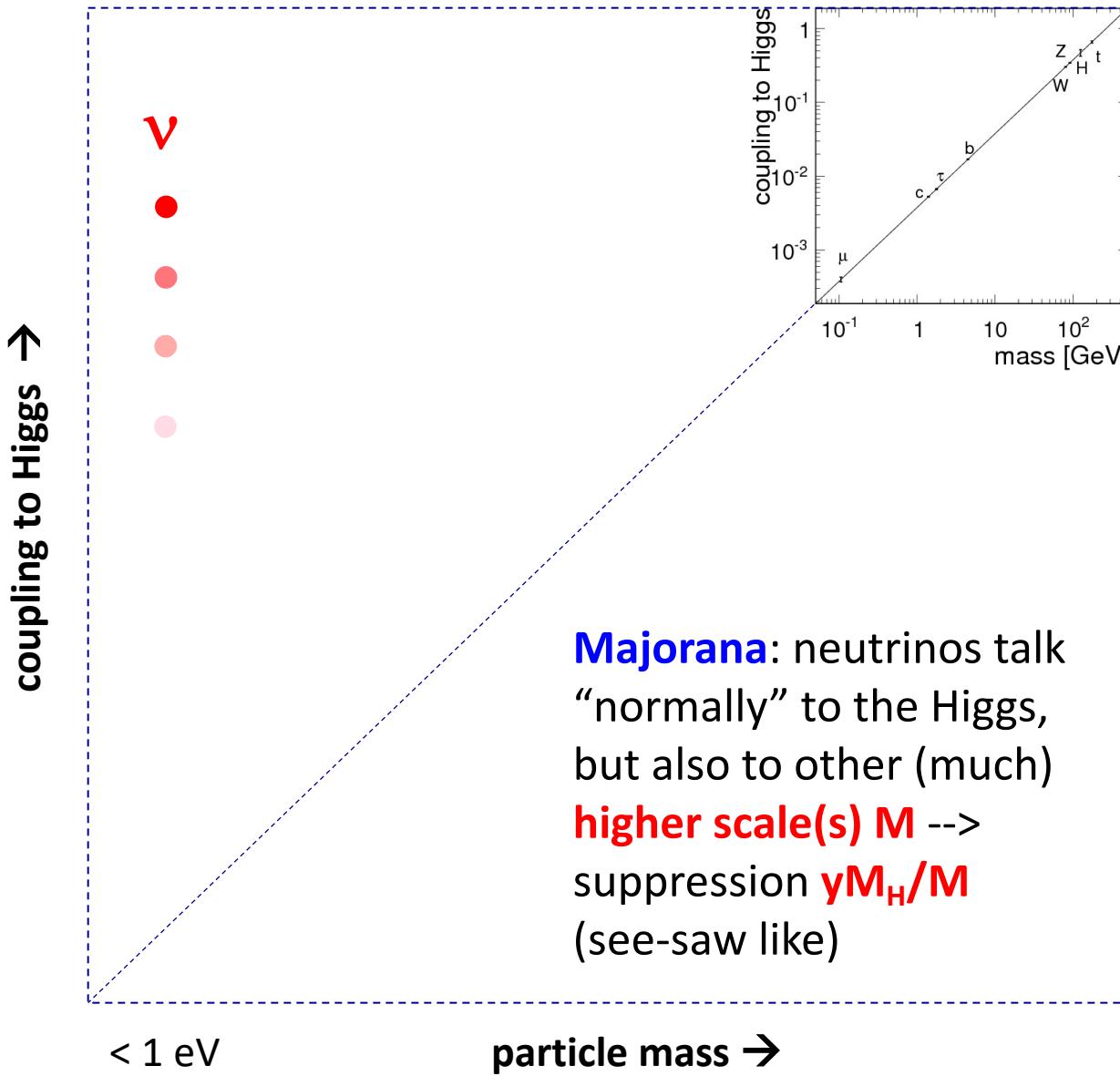
particle mass →

Dirac: neutrinos “talk”
very weakly to the
Higgs boson, $y < 10^{-12}$
for unknown reasons...

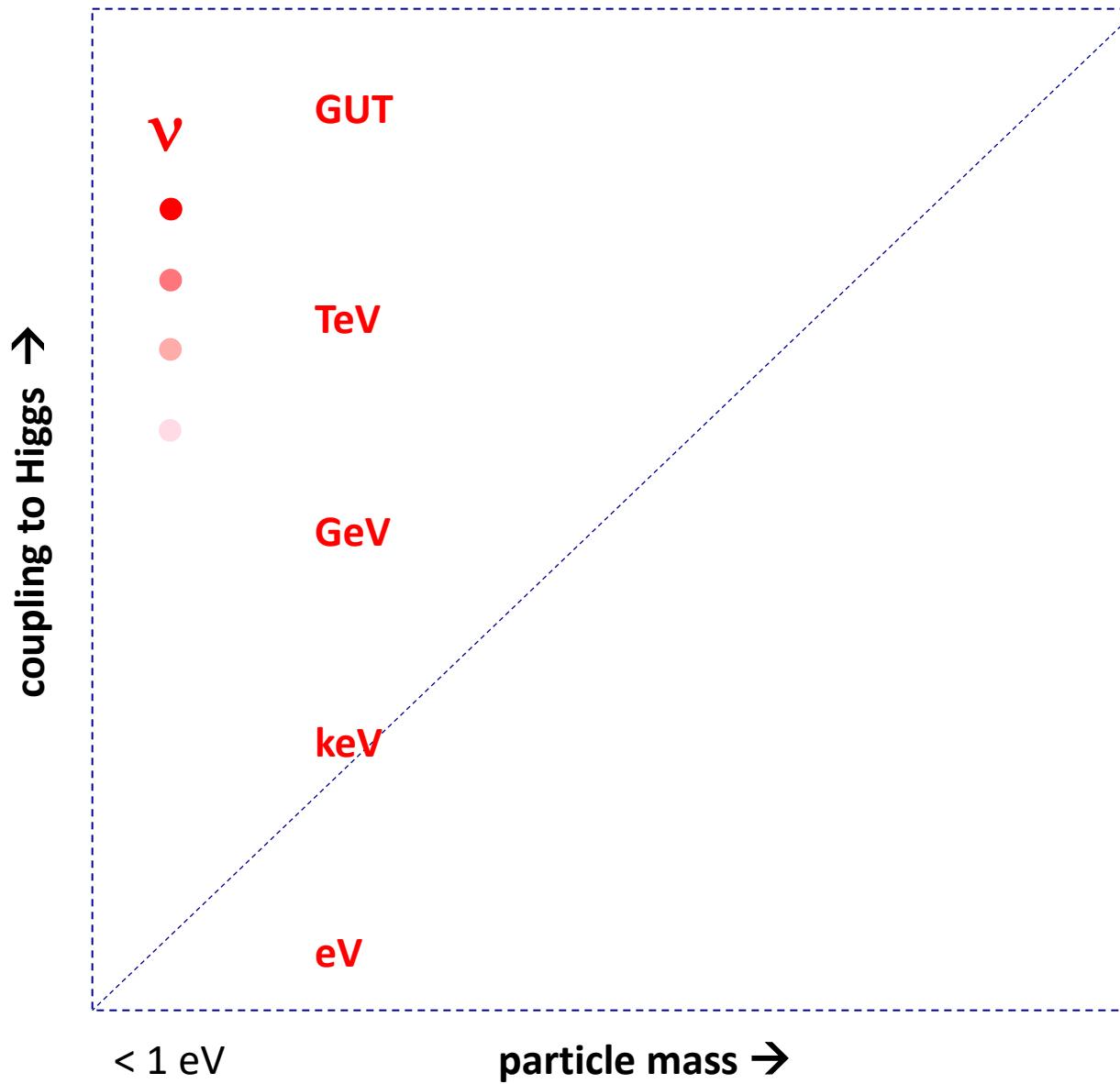
ν



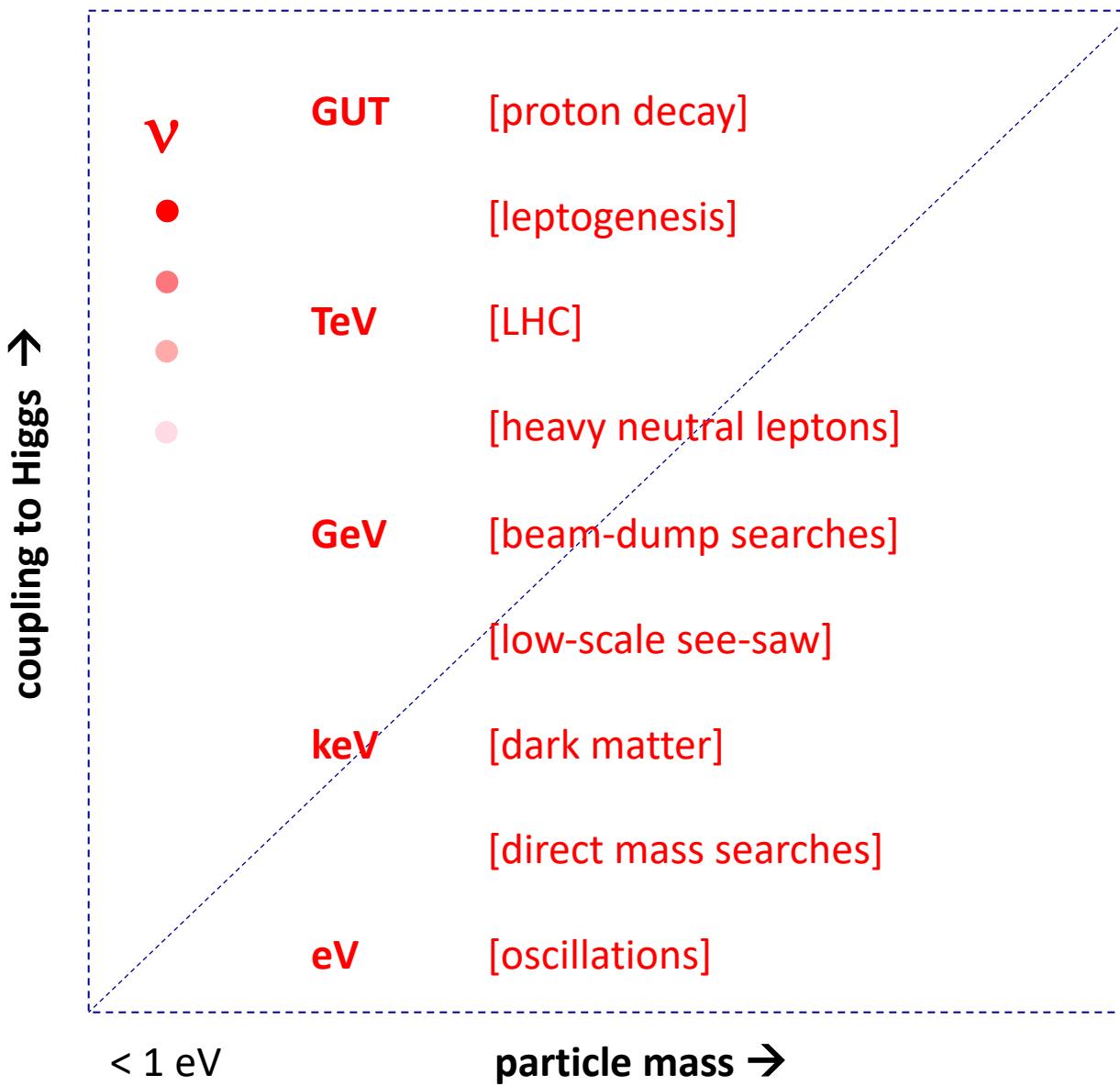
Options:



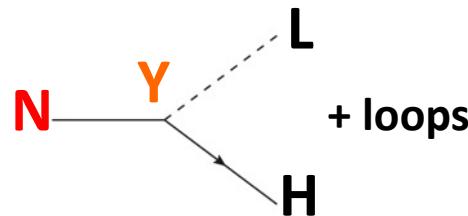
...New mass states could emerge at different new scales ...



... and contribute to a wide research program with HE/LE links...



E.g. Leptogenesis: C, CP, L-violating and out-of-equilibrium decays of heavy N at $T \sim M_N$ can generate lepton asymmetry $\Delta L \rightarrow$ non-perturb. $\rightarrow \Delta B$ (BAU)



with: $\Gamma(N \rightarrow L) \neq \Gamma(N \rightarrow \bar{L}) \rightarrow \Delta L$

via: $Y \sim U_\nu m_\nu^{1/2} \frac{1}{v} U_N M_N^{1/2}$

Involves masses, mixing, phases at both high (N) and low (v) scales.

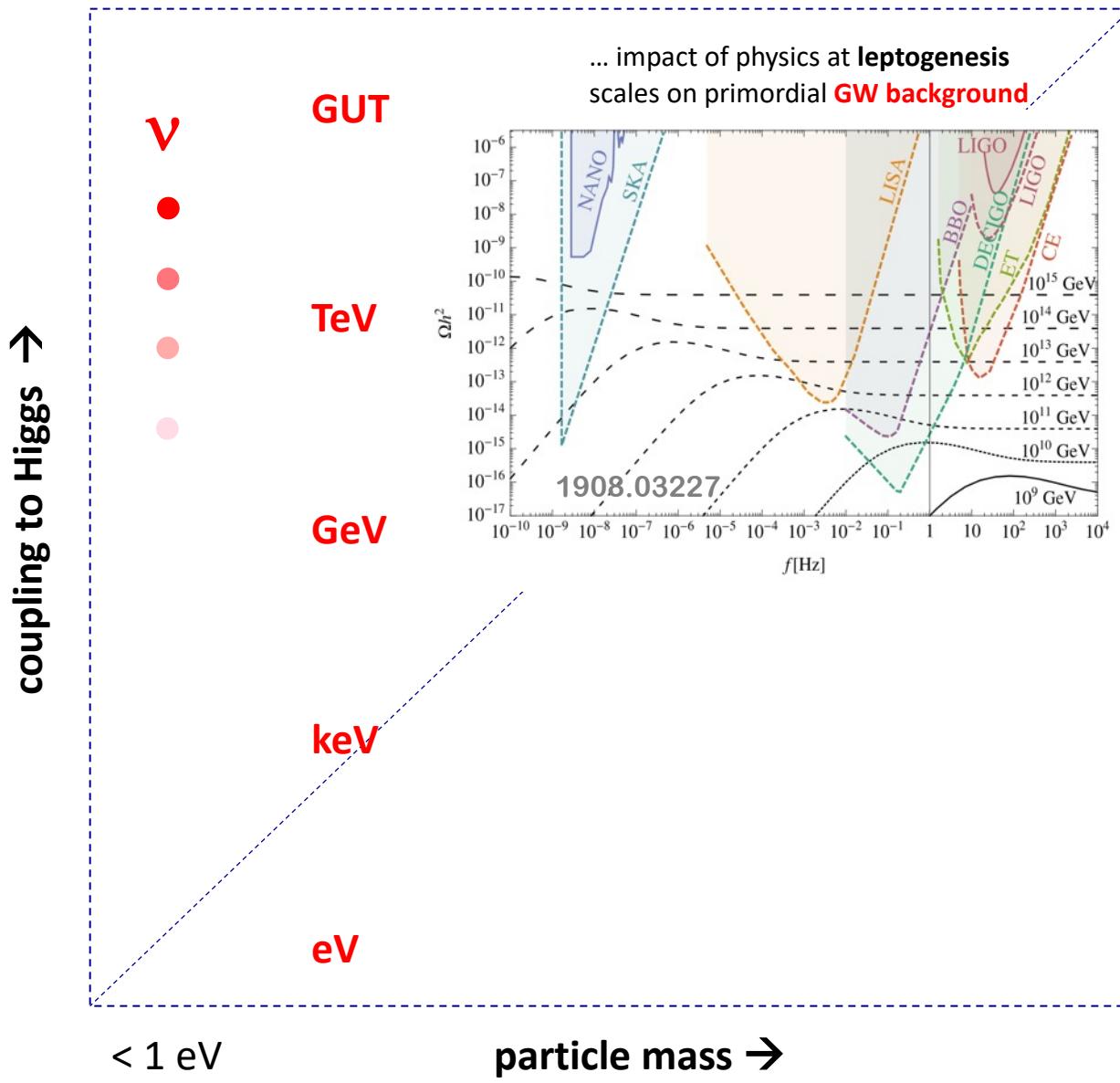
Involves (non)equilibrium evolution in an expanding & cooling universe.

Significant work to assess/extend ranges of M (and T) of successful models

At high scale: Typical models work from $M \sim 10^{14}$ down to $\sim 10^6$ GeV.
In tuned models (e.g., \sim degenerate masses) can lower to $M \sim v$ (EW)
 \rightarrow make contact with heavy N searches and $0\nu\beta\beta$ decay

At low scale: In a wide range $M \sim 10^{8(6)} - 10^{13}$ GeV, leptogenesis can also be realized just via PMNS phase δ (and/or Majorana α, β)
 \rightarrow make contact with low-energy CPV and $0\nu\beta\beta$ decay

+ further links still to be explored in the long term...



?

▼

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Thank you
for your attention!

Extra slides

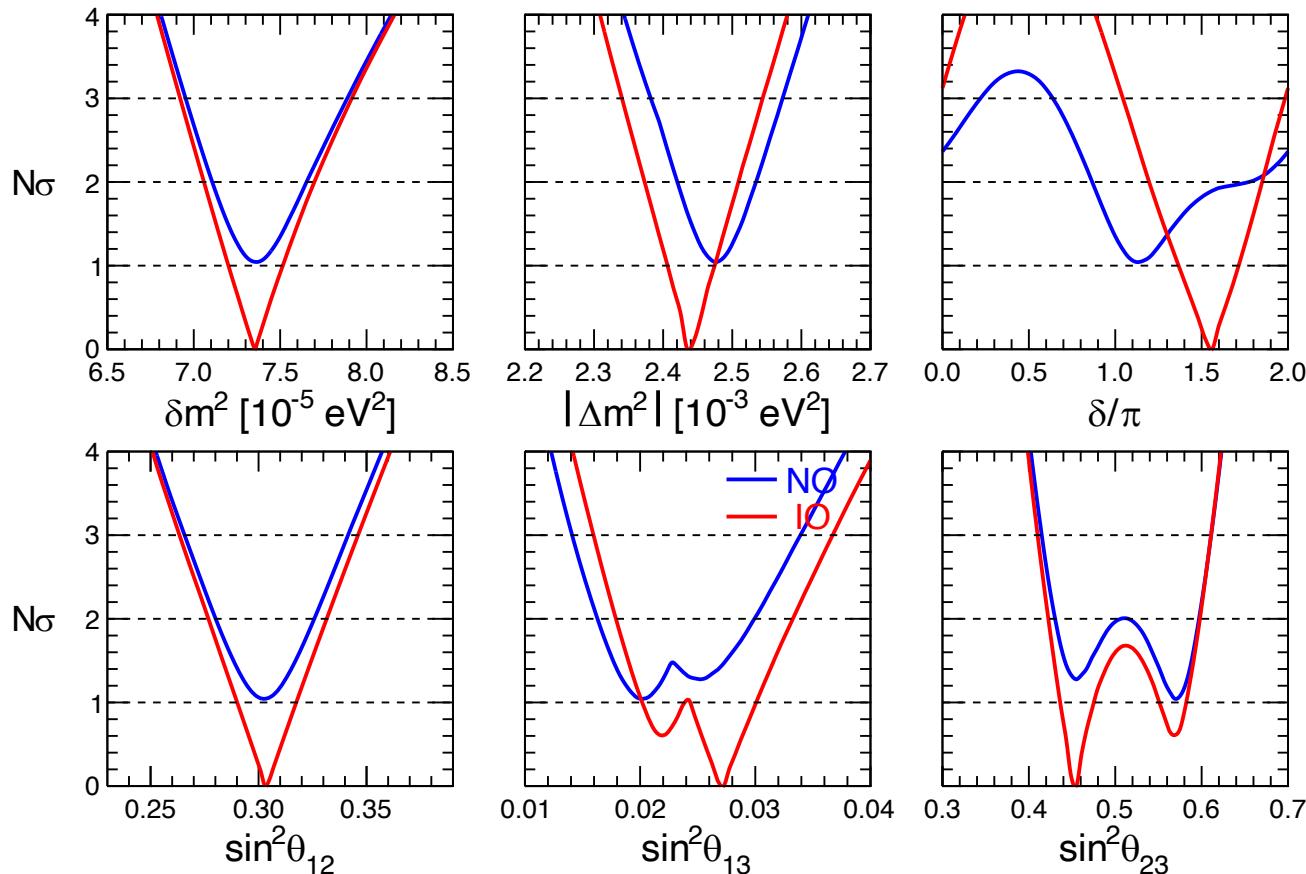
Summary of known and unknown 3 ν oscillation parameters, circa 2021

TABLE I: Global 3 ν analysis of oscillation parameters: best-fit values and allowed ranges at $N_\sigma = 1, 2$ and 3 , for either NO or IO, including all data. The latter column shows the formal “ 1σ fractional accuracy” for each parameter, defined as $1/6$ of the 3σ range, divided by the best-fit value and expressed in percent. We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that $\delta \in [0, 2\pi]$ (cyclic). The last row reports the difference between the χ^2 minima in IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“ 1σ ” (%)
$\delta m^2/10^{-5}$ eV 2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2 \theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$ \Delta m^2 /10^{-3}$ eV 2	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2 \theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2 \theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+6.5				

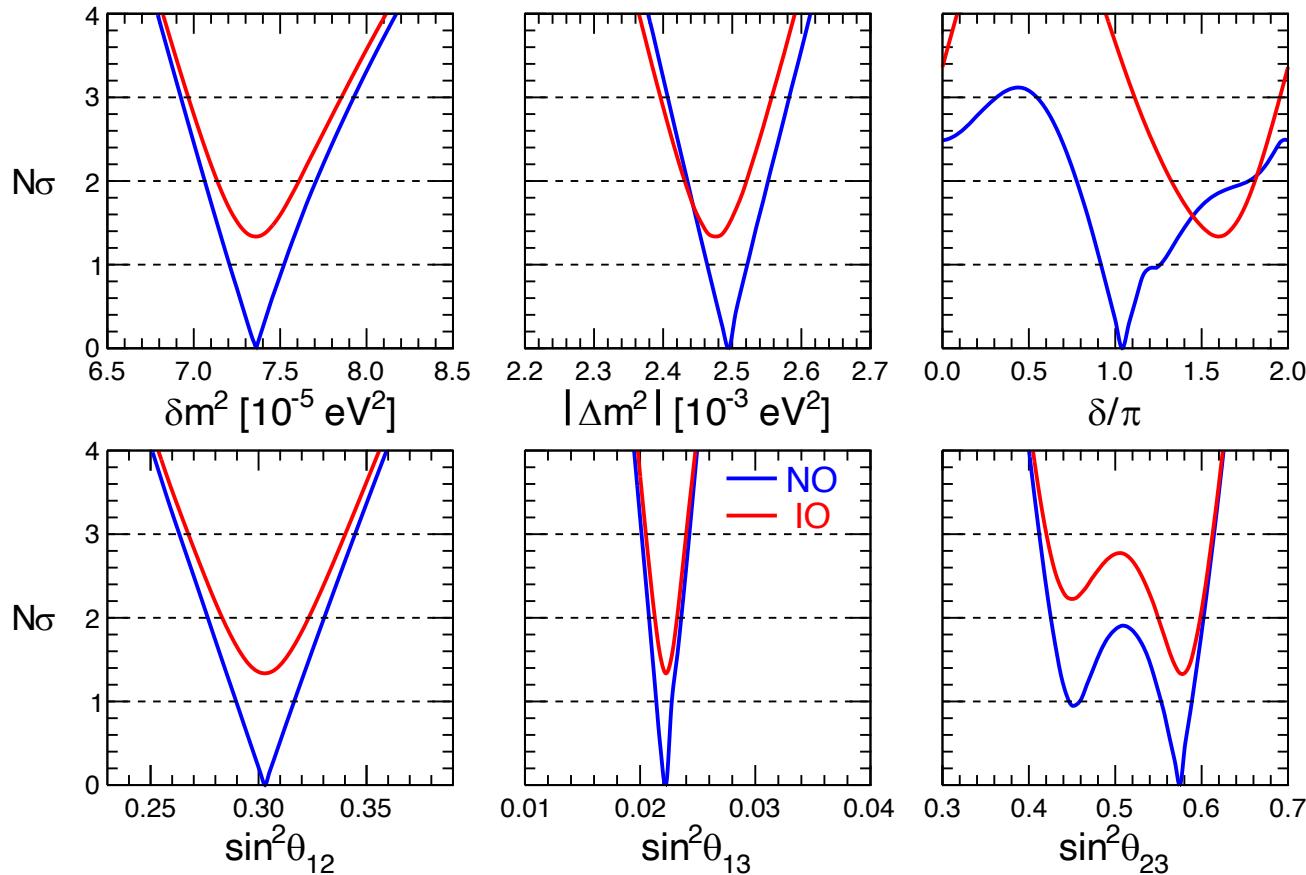
hep-ph 2107.00532

LBL Acc + Solar + KamLAND



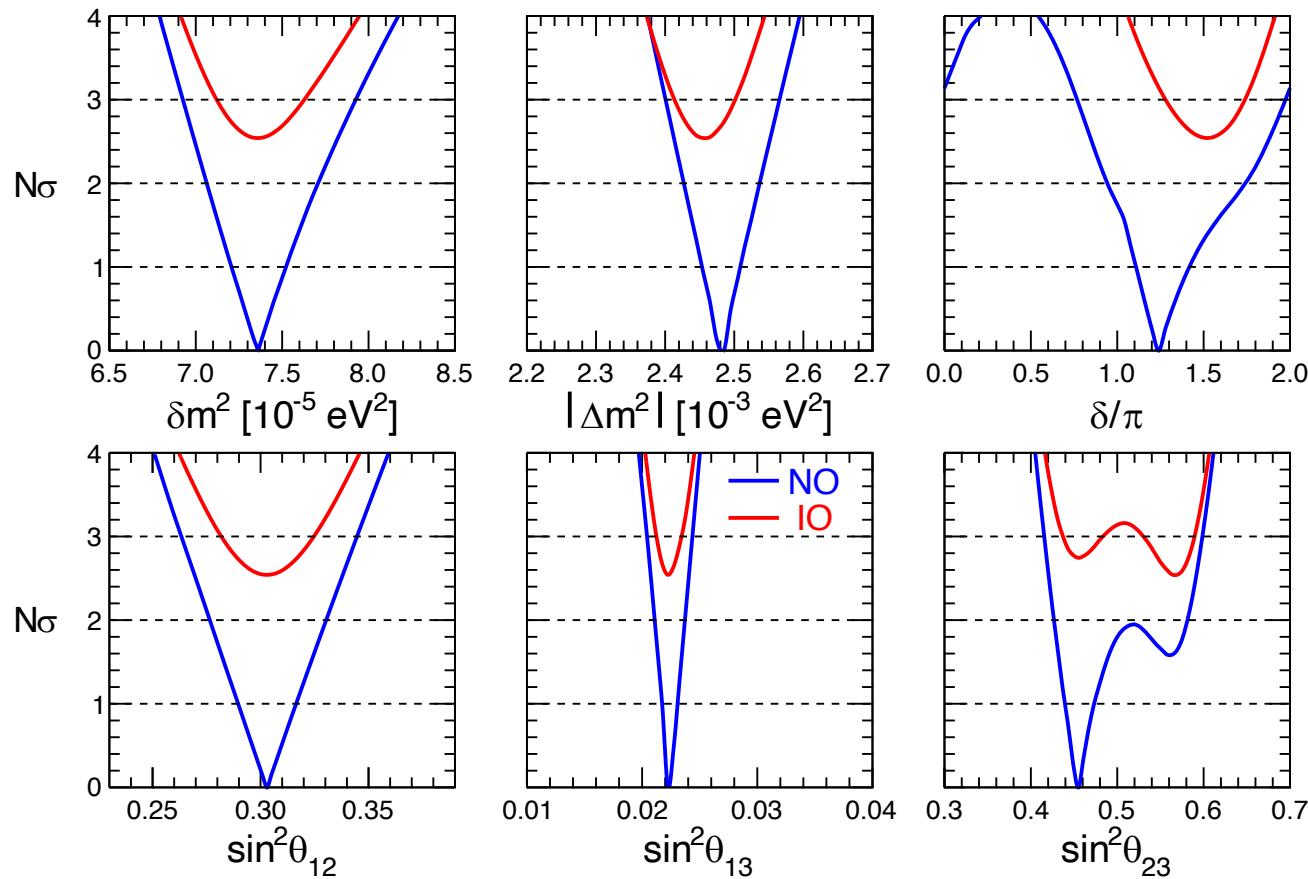
- Upper and lower bounds at $>>3\sigma$ for δm^2 , Δm^2 , θ_{12} , θ_{13} , θ_{23}
- Weak preference for **IO** at $\sim 1\sigma$. Note different Δm^2 in NO/IO
- Octant degeneracy of θ_{23} also affects θ_{13} via correlations in $\nu_\mu \rightarrow \nu_e$
- Preference for $\delta \sim 3\pi/2$ (CP violation) in **IO**, but not in NO

LBL Acc + Solar + KamLAND + SBL Reactors



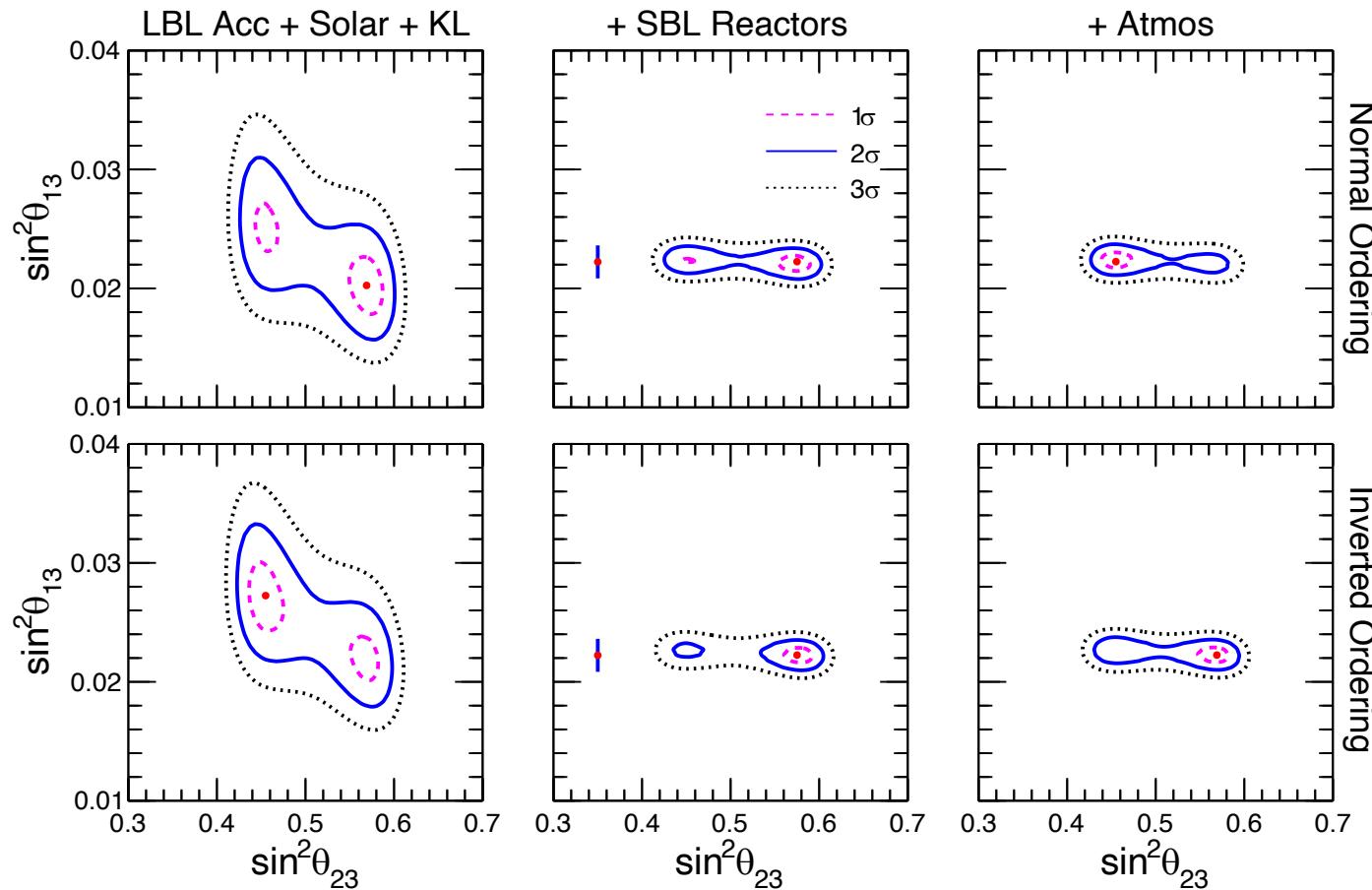
- Bounds on θ_{13} and Δm^2 strengthened
- Preference for **NO** at $\sim 1.5\sigma$. Note overall higher Δm^2 in both NO and IO
- Octant degeneracy of θ_{23} weakly broken, **2nd octant** preferred at $\sim 1\sigma$
- Preference for $\delta \sim \pi$ (CP conservation) in **NO**, while $\delta \sim 3\pi/2$ in IO

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



- Increased preference for **NO** (2.5σ)
- Preference flips to **1st octant** of θ_{23} (1.6σ)
- CP phase: best fits around $\delta \sim 1.2\pi$ in **NO** and $\delta \sim 3\pi/2$ in **IO**

$(\theta_{13}, \theta_{23})$ covariance

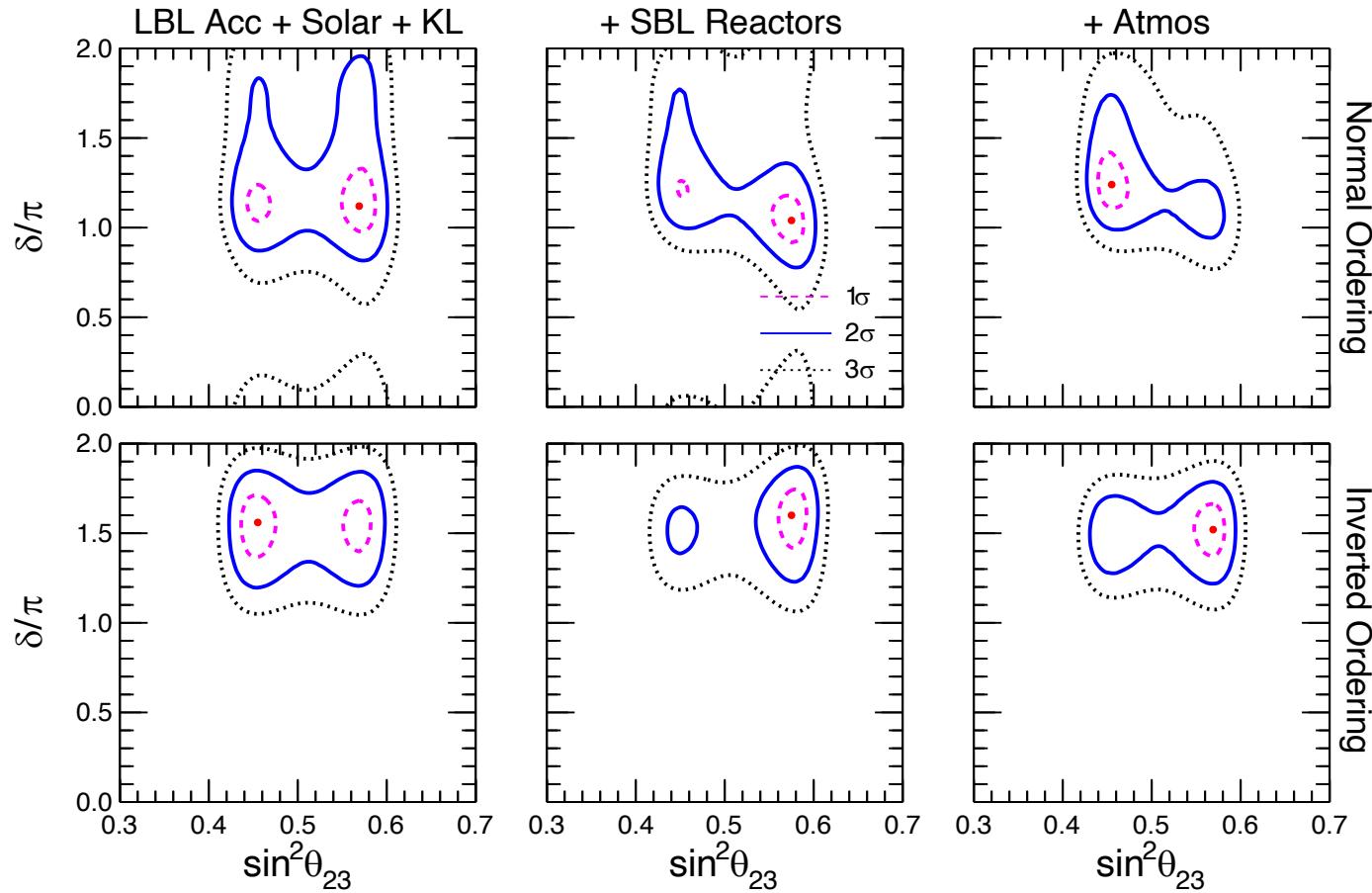


Anticorrelation due to
leading $\nu_\mu \rightarrow \nu_e$ term
 $\sim \sin^2 \theta_{23} \sin^2 2\theta_{13}$

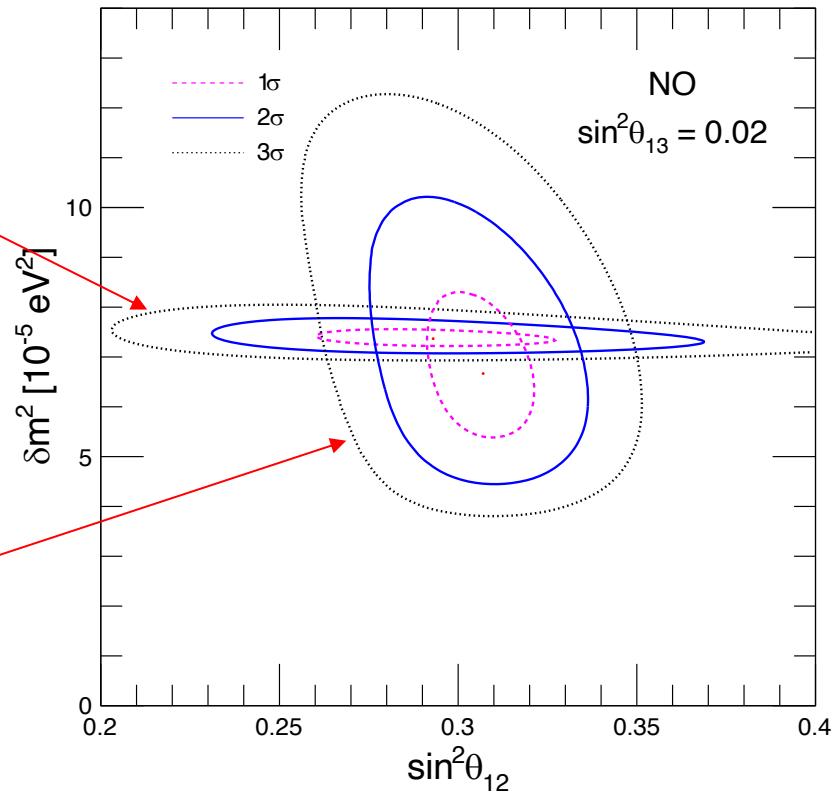
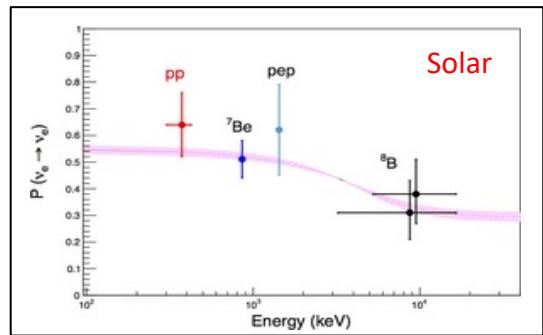
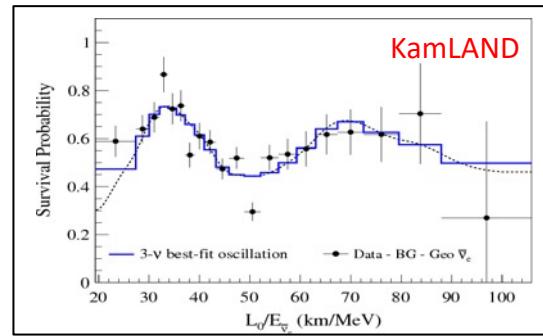
Narrow and “low” θ_{13}
reactor angle
selects 2nd octant

1st octant preferred
by atmospheric data
in NO (not in IO)
→ fragile!

(δ, θ_{23}) covariance



$(\delta m^2, \theta_{12})$ pair: a success story $\rightarrow (\nu_1, \nu_2)$ param. + MSW effect + Sun (pp+CNO)



Progress: MBL reactors (JUNO) \rightarrow precision frontier on both oscill. parameters
Large-volume solar ν detect. \rightarrow precision MSW in Sun + Earth (D/N)
 Lack of consistency may reveal new physics (e.g., NSI)

Bounds on Σ

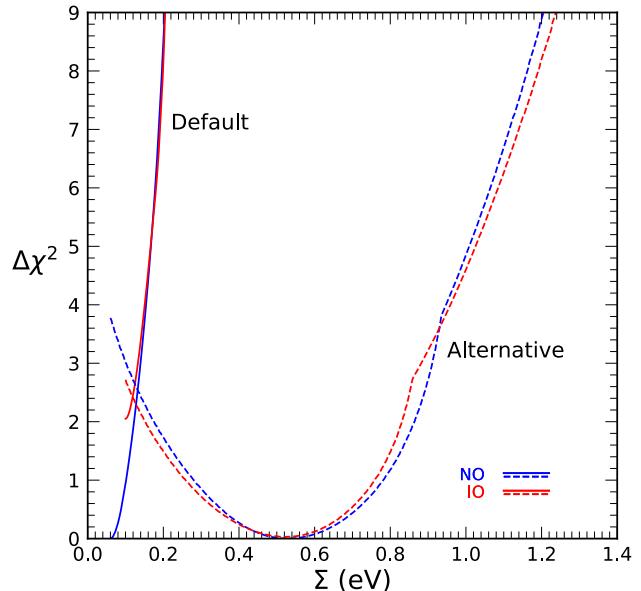
Cosmology: data / model variants

TABLE IV: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\text{CDM} + \Sigma$ model (possibly augmented with the A_{lens} parameter). The inputs numbered from 0 to 9 are the same as in [11], and refer to various combinations of the Planck 2018 angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), lensing potential power spectrum (lensing), Barion Acoustic Oscillations (BAO), and the Hubble constant from HST observations of Cepheids in the Large Magellanic Cloud, H_0 (R19). The inputs numbered from 10 to 12 are new and refer to ACTPol-DR4 and WMAP9 data, in combination with a prior on optical depth to reionization (τ_{prior}), Planck polarization data at large angular scale (lowE), and lensing data. For each case we report the 2σ upper bound to the sum of ν masses Σ (marginalized over NO and IO), together with the $\Delta\chi^2$ difference between IO and NO, using cosmology only. In the last two columns, we report the same information as in the previous two columns, but using cosmological data plus m_β and $m_{\beta\beta}$ constraints. The specific cases numbered 3 and 12 are dubbed as default and alternative, see the text for details.

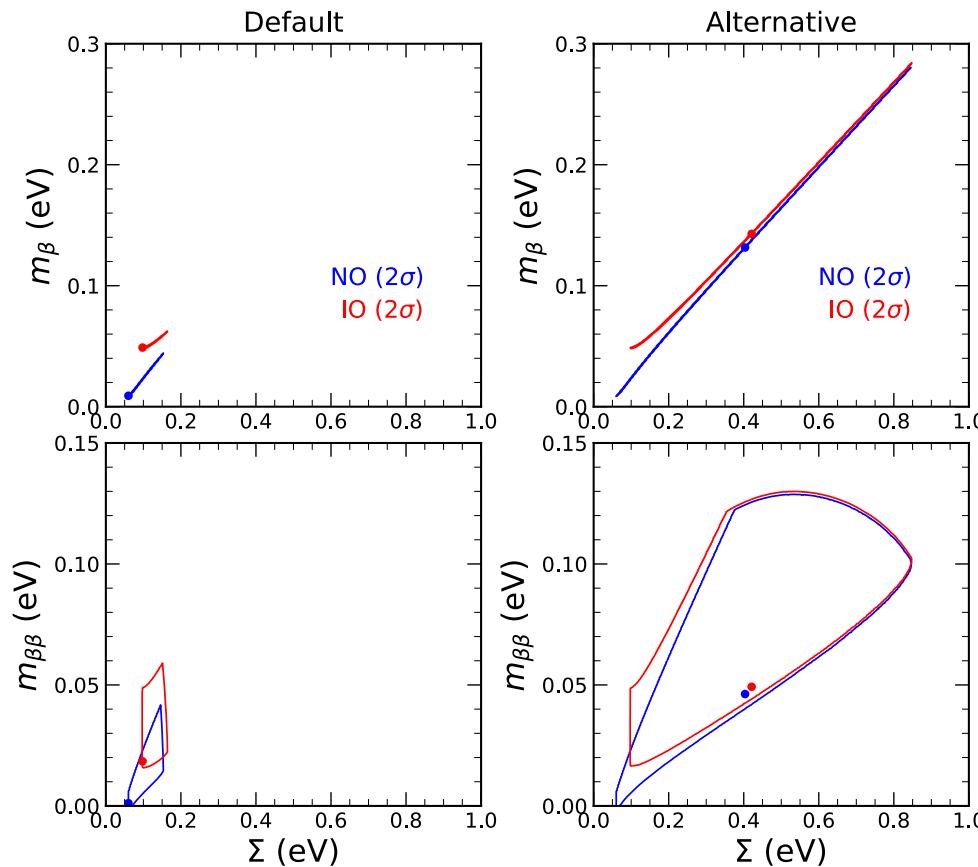
Cosmological inputs for nonoscillation data analysis		Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$		
#	Model	Data set	Σ (2 σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2 σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing + H_0 (R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + H_0 (R19)	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing + H_0 (R19)	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + τ_{prior}	< 1.21 eV	-0.1	< 1.00 eV	0.1
11	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE	< 1.12 eV	-0.1	< 0.87 eV	0.1
12	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

(Default = #3, Alternative = #12)

Representative cases

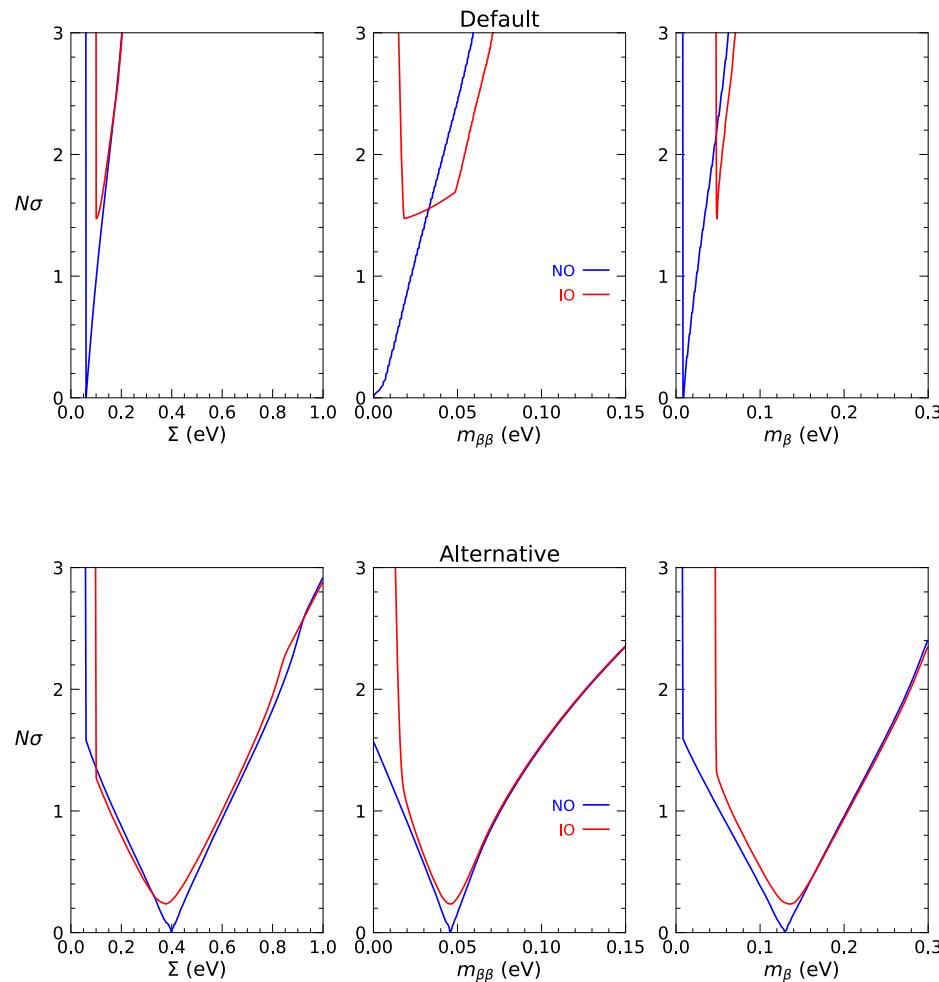


Joint bounds on (m_β , $m_{\beta\beta}$, Σ)



hep-ph 2107.00532

Separate bounds on (m_β , $m_{\beta\beta}$, Σ)



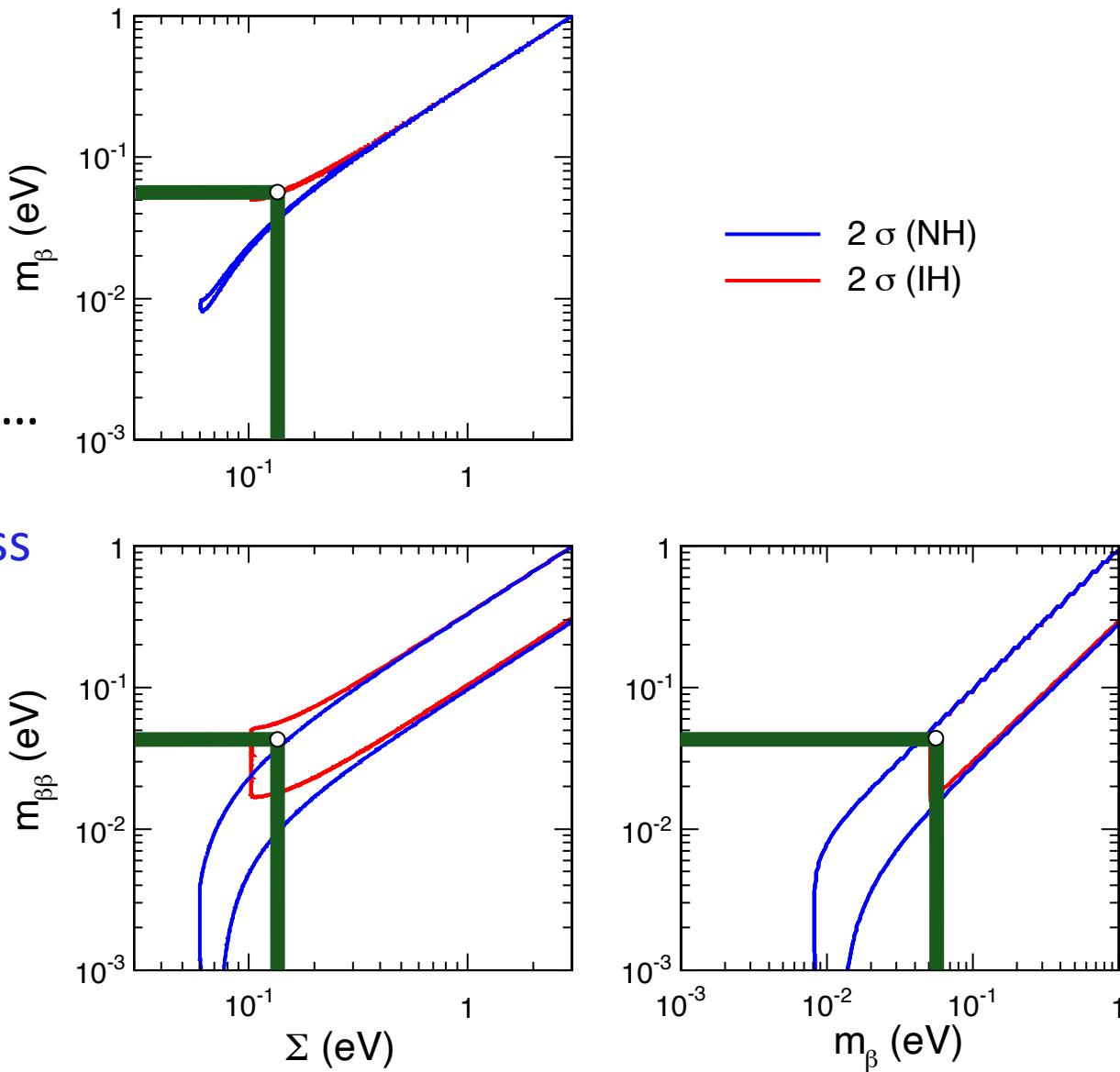
Far future: with precise and converging non-oscillation signals one could...

Determine the mass scale...

Check 3ν consistency ...

Identify mass ordering ...

Probe the Majorana phase(s) ...



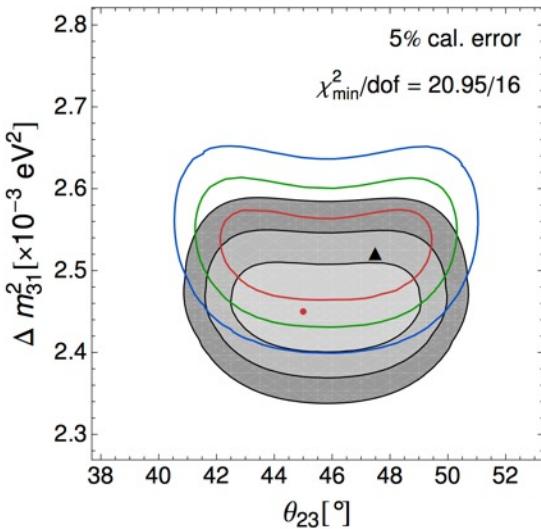
Neutrino-nuclear interactions and LBL accelerator experiments

Cross section uncertainties may affect:

Δm^2 (via E_{rec}), θ_{23} (via spectral norm+shape), δ (via $\nu-\bar{\nu}$ interaction differences)

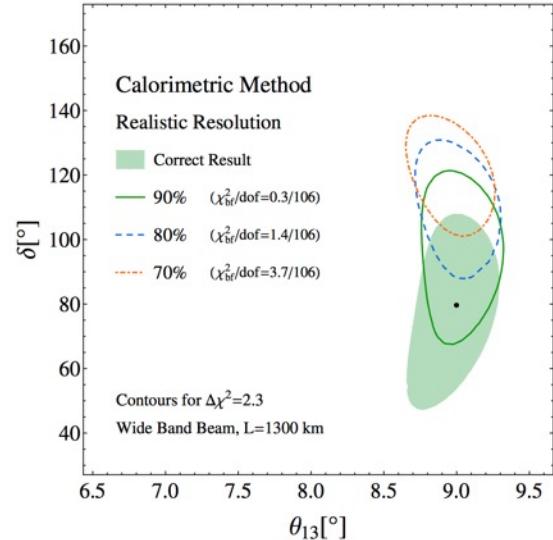
Exercise to estimate bias:

Generate data with one Xsec model and analyze them with a different model



← Biased →
ranges of
 $\Delta m^2, \theta_{23}$
 δ

[Benhar+ 1501.06448,
Alvarez+ 1706.03621,
and refs. therein]



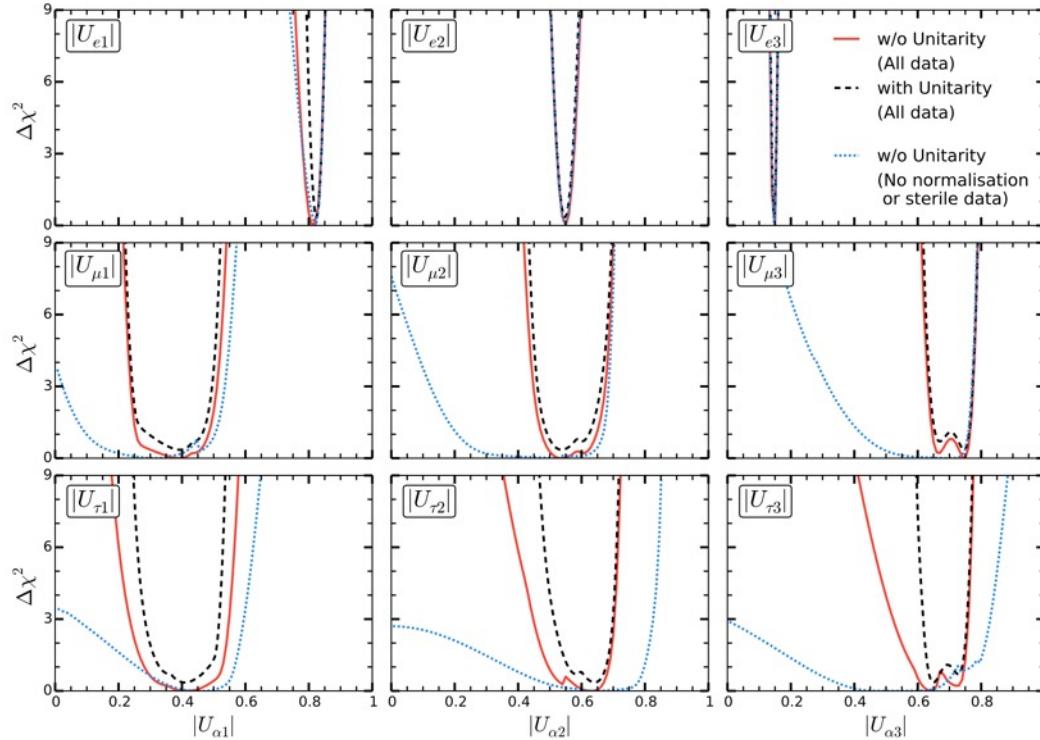
Effects reduced -but not zeroed- by tuning model(s) to ND data.

Remind: No model currently explains all available Xsection data!

Current 1% global-fit formal accuracy on Δm^2 might be optimistic

Progress on flux and cross section predictions also needed to get precise absolute normalizations of events → important for “unitarity” tests
 [“leakage” of PMNS elements embedded in a matrix larger than 3x3]

E.g., Parke & Ross-Lonergan 1508.05095, model-independent



**Stronger constraints by assuming specific models for new (sterile) neutrino states
...which might appear anywhere from the ~eV scale (hints?) to the GUT scale!**

Surprises may include not only extra states, but also new interactions

There is much more than just cross sections for LBL accel. expts!

Need to know better the nuclear response to EW probes in various contexts

Beta decays for nuclear reactor spectra

Coherent Elastic Neutrino
Nucleus Scattering

Charge exchange processes for DBD NME

Neutrinos in very dense fermion
backgrounds (SN, mergers, early universe)

Effective neutrino axial current:
coupling strength and form factors

Nuclear astrophysics and neutrinos
(nucleosynthesis & solar reactions networks)

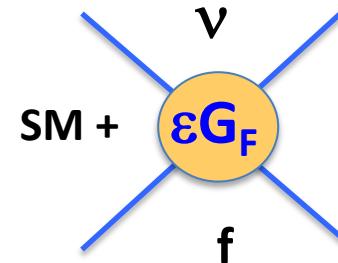
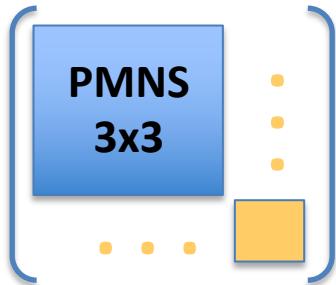
EFT vs QCD

Ab initio nuclear structure

Connections with other EW probes
(gammas, electron, possible WIMPs...)

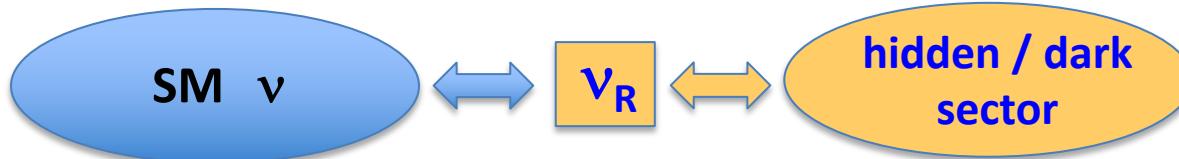
Stress-tests of the 3 ν paradigm

Testing the resilience of the 3 ν paradigm to **extra ν states** or to **new interactions**:
Approach often involves PMNS unitarity violations or nonstandard FCNC, FDNC (NSI)



Extra parameters may dilute hints of PMNS unknowns: CPV, θ_{23} octant, ordering.
Rich phenomenology in (non)oscillation experiments + astrophysics & cosmology
No evidence so far, except possible **O(eV) sterile ν** anomalies [not discussed here]

Going further: consider both extra states and interactions: RH neutrinos as a **bridge** (“portal”) to weakly coupled **BSM physics** (“hidden” or “dark” sector), e.g. **DM**



Low-scale BSM “portal” scenarios can provide new stress tests of the 3 ν paradigm (as well as of 3 ν +1 ν_s models), e.g. via **modified neutrino dispersion relations**.

Mixings: Many interesting ideas, but still looking for an “illumination”...

No organizing principle
 (“anarchy”)



Discrete family symmetries
 (“geometry”)

linear relations between
 $\theta_{13}\cos\delta$ and θ_{12}, θ_{23}

Continuous flavor symmetries
 (“dynamics”)

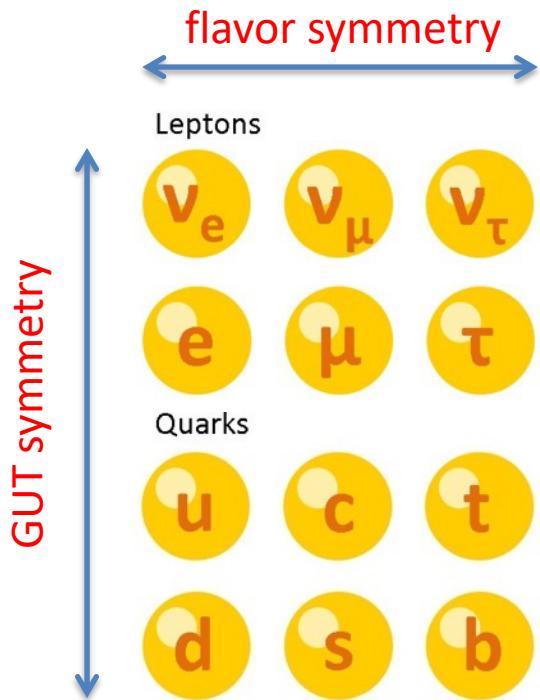
links between neutrino
 masses/angles/phases

Common quark-lepton features
 (“complementarity”)

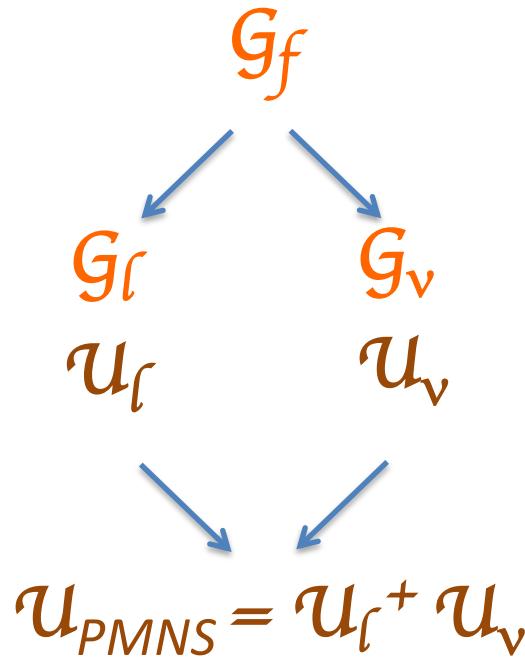
links between
 θ_{13} and θ_c

Model building with symmetries

New high scale(s) with higher symmetries



Flavor symmetries:
group patterns



$$GUT \rightarrow U_l \approx \mathcal{V}_{CKM}$$

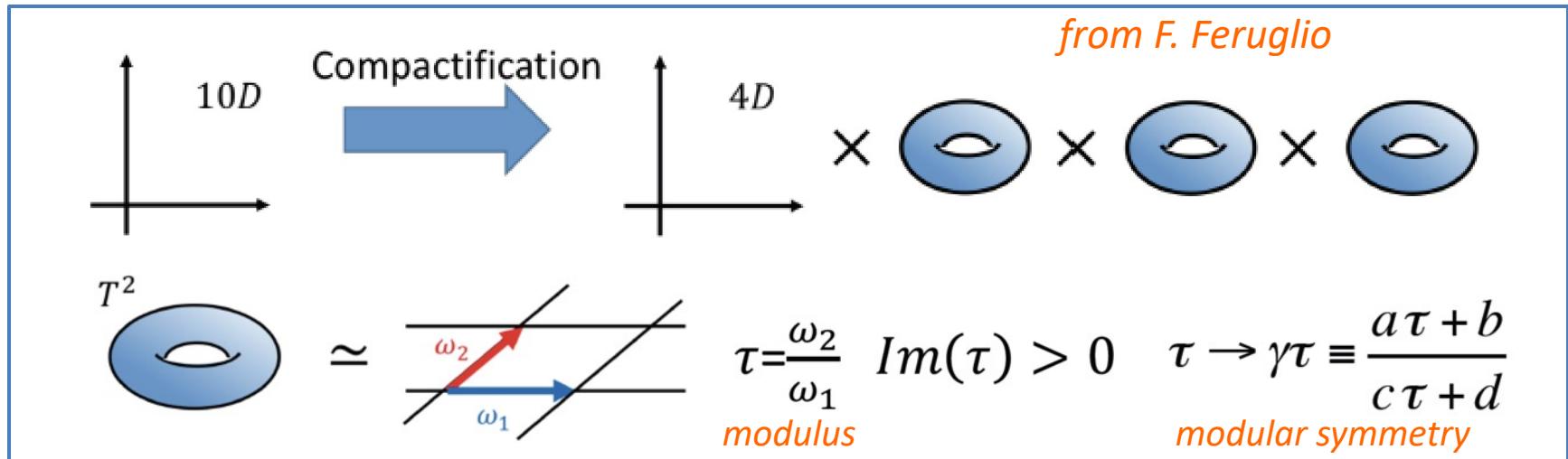
Examples:

$$G \leftarrow \text{Permutations}$$

Occam's razor?

Symmetry models often involve a large and carefully crafted scalar sector (e.g., flavons + vev's)

Can symmetries emerge in a “more economical” way? Yes! E.g.: Modular Invariance
 [inspired by string theory & compactified extra dimensions; requires supersymmetry.]

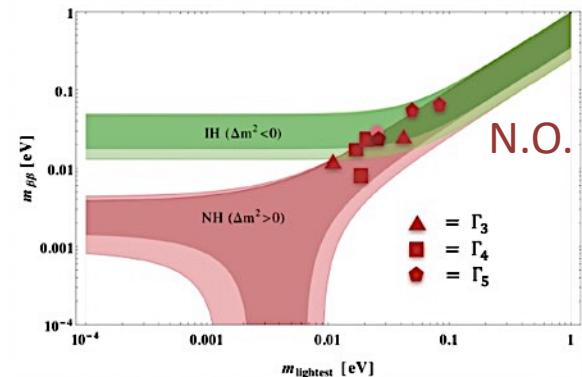


Yukawa's $Y=Y(\tau)$ become highly symmetric/constrained:

obtain masses, mixings and phases
 with # parameters < # observables

→ predictions, e.g., →

Recently: extend modular invariance to all fermions' Y



Time-honored ideas continue to illuminate the path forward!

perspective

NATURE PHYSICS | VOL 14 | FEBRUARY 2018

Symmetry and emergence

[Edward Witten, arXiv:1710.01791]

In a modern understanding of particle physics, global symmetries are approximate and gauge symmetries may be emergent. This view, which has echoes in condensed-matter physics, is supported by a variety of arguments from experiment and theory.

No reason for global symmetries to be exact, from different theoretical perspectives.

No global lepton number conservation

$$\mathcal{L}_1 = \frac{1}{M} H H L L$$

Majorana neutrinos, $\nu = \bar{\nu}$

No global baryon number conservation

$$\mathcal{L}_2 = \frac{1}{M^2} Q Q Q L$$

Proton decay

No a priori CP conservation in QCD

$$\frac{\theta}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} \text{tr } F_{\mu\nu} F_{\alpha\beta}$$

Axion

General arguments not weakened by absence of new physics at the LHC scale.
Any of these three possible discoveries would be a historical landmark in science.

In particular: Majorana ν

may offer a great opportunity
to probe **a scale $M \gg v$ (EWSB)**
via the see-saw mechanism...

$$\mathcal{L}_1 = \frac{1}{M} H H L L$$

M (same as GUT
and p-decay?)



v

heavy **N**

light **v**

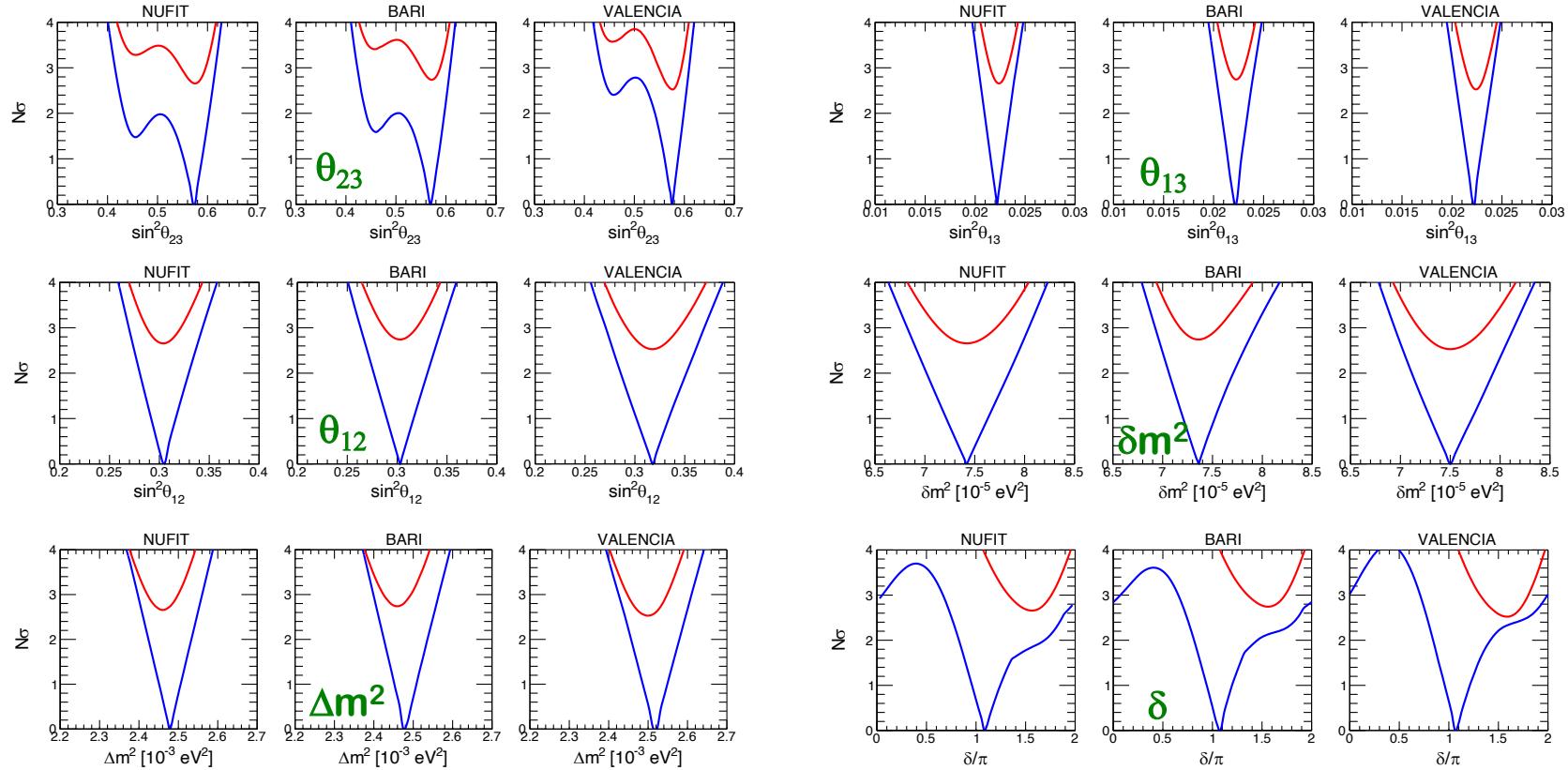
$$m(v) \sim Y^2 v^2 / M$$



... and to address fundamental physics issues, such as:

- lepton number violation and associated phenomena ($0\nu\beta\beta$)
- new sources of CP violation at low and high scales
- baryon (matter-antimatt.) asymmetry of the universe (BAU)...

Comparison among independent global neutrino oscillation data analyses



BARI:

2003.08511

NUFIT:

2007.19742

[with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

VALENCIA:

2006.11237v2

[with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]